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EFFECTS OF CLEARCUTTING ON NUTRIENT CYCLING IN LODGEPOLE PINE FORESTS

by
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Effects of Clearcutting on Nutrient Cycling In Lodgepole Pine Forests

By

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PREFACE

This report constitutes the "Final Report" of studies conducted between June 1971 and October 1974, on the effects of clearcutting on nutrient cycling in lodgepole pine forests. This research was supported by United States Forest Service Contracts P. O. No. 663-RM-71 and P. O. No. 663-RM-71 Sub-1, and Research Agreements 16-256-GR (1972) and 16-324-GR (1973-74). Administration of the Contracts and Research Agreements was conducted by the U. S. Forest Service Rocky Mountain Forest and Range Experiment Station, Karl F. Wenger, Director. We wish to acknowledge the valuable support and assistance during these studies of Dr. Marvin D. Hoover and Dr. Carl Berntsen, both of the Rocky Mountain Forest and Range Experiment Station,and Dr. Herbert A. Schroeder, Department of Forest and Wood Sciences. We further wish to acknowledge the use of the following laboratory facilities at Colorado State University: Colorado Cooperative Fishery Unit, Wood Sciences Laboratory, and the Department of Agronomy.

The research reported here was used in partial fulfillment of the requirements for the degrees of Doctor of Philosophy at Colorado State University, for J. C. Hokenstrom and G. J. Odegard.

ABSTRACT

Soils and forest floor, lodgepole pine trees, understory vegetation, logging residues and subsurface water from three 3.4 ha treatment sites were described and analyzed to determine the effect of clearcut forest harvesting on biomass and certain chemical properties. One site served as an undisturbed forest control, while two sites were clearcut on different dates, one in 1965 and one in 1972.

Soil profile characteristics recorded were color, texture, structure, consistency, thickness, content of roots, and stoniness. Chemical properties analyzed were percent organic matter, pH, cation exchange capacity, percent total nitrogen, nitrate-nitrogen, available phosphorus, and exchangeable potassium, calcium, and magnesium. Lodgepole pine trees, understory vegetation, and logging residues were analyzed for total nitrogen, phosphorus, potassium, and calcium. Biomass determinations were made for each of these ecosystem components.

Mineral soil horizons (A2 and B2) exhibited low fertility as expected in forest soils. Nutrient levels in soils of the 1972 clearcut showed no detectable response to clearcutting. Mineral soils of the 1965 clearcut site had lower available phosphorus and percent organic matter levels, and higher pH, exchangeable calcium, and exchangeable magnesium levels. Forest floor horizons of the 1965 clearcut had lower levels of total nitrogen, nitrate-nitrogen, and potassium. Clearcutting almost doubled the 01 horizon biomass of the 1972 clearcut, while the 02 horizon biomass in the 1965 clearcut was about half that in the other two sites.

Understory vegetation in the 1965 clearcut accumulated from two to nine times more nitrogen, phosphorus, potassium, and calcium than corresponding vegetation in the other sites. This was due both to greater total biomass and higher nutrient levels of understory vegetation in the 1965 clearcut. Clearcutting the 1972 clearcut site reduced total understory biomass by 52 percent.

Logging residues from the 1965 clearcut had lost much of their original nitrogen and phosphorus contents, and most of their potassium and calcium contents by seven years after clearcutting. 1972 clearcut logging residues had nutrient contents similar to live lodgepole pine trees, and had about four times the biomass of the 1965 clearcut logging residues.

Nutrient reserves in the upper 30.5 cm of mineral soil were from six to 13 times greater than amounts removed in a conventional clearcut harvest at the end of a 200-year rotation. The amount of nutrients removed by the harvest of the 1972 clearcut site represented eight percent of the total soil nitrogen, 11 percent of the available soil phosphorus, 16 percent of the exchangeable soil potassium, and six percent of the exchangeable soil calcium.

Water quality was examined by collecting soil-water samples from below the rooting zone with tube-tension lysimeters on each of the three sites. Sampling was conducted from late-May to early October, 1973, and from mid-May until the end of July in 1974.

Average amounts of water collected from the new and old clearcuts were 86 and 59 percent greater, respectively, than from the control during 1973, and 20 percent greater during 1974.

When compared to the forested control site, average soil-water concentrations during 1973 were higher from the new clearcut by 79 percent for NO_3^-, 58 percent for Ca^{++}, 8 percent for K^+, 79 percent for $SO_4^=$, and 33 percent for PO_4^{-3}. There was no change in sodium concentration, but a 42 percent decrease in NH_4^+ and a 32 percent decrease in Cl^- were noted. During the sampling period in 1974, the new clearcut concentrations were higher than the forested control by 1079 percent for NO_3^-, 93 percent for Ca^{++}, 71 percent for Mg^{++}, 57 percent for K^+, and 21 percent for Na^+.

Average concentrations in 1973 from the old clearcut were greater than from the control by 711 percent for NO_3^-, 50 percent for Ca^{++}, 23 percent for K^+, 13 percent for Na^+, 24 percent for $SO_4^=$, and 50 percent for PO_4^{-3}. Concentrations of NH_4^+ and Cl^- were 50 and 59 percent lower, respectively. During 1974, the old clearcut concentrations were greater than the forested control by 672 percent for NO_3^-, 27 percent for Ca^{++}, 57 percent for Mg^{++}, 29 percent for K^+, and 14 percent for Na^+.

Data suggest that following clearcutting of lodgepole pine forests, significant losses of nutrients can be expected for at least nine years after cutting. Implications of nutrient additions to streams draining clearcut areas are discussed.

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INTRODUCTION

Approximately one-third of the land surface of the United States is forested, and much of it is occasionally harvested. Clearcutting is the dominant practice in timber harvesting and forest management operations in the Rocky Mountains, and in 1970 accounted for 80 to 85 percent of the total timber harvest area (Dils, 1971). Clearcutting refers to the removal of an entire stand of trees in one cut, and is often considered the only feasible timber harvesting method for regenerating lodgepole pine *(Pinus contorta* Dougl. var. *latifolia)* Engelm.) (Wellner, 1971), a valuable sub-climax forest type in the Rocky Mountains of the Western United States.

The practice of clearcutting mature forests in order to harvest standing timber and to create young even-aged second growth has recently come under attack. Questions have been raised, including whether clearcutting creates conditions that lead to loss of nutrients needed to assure future crops of trees, and whether this practice is compatible with long-term sustained yield forest management (Bormann et. al., 1968; Likens, Bormann, and Johnson, 1969; Curry, 1970, 1973; Likens et al., 1970; Bolle et al.,1970; Fredriksen, 1971; U. S. Forest Service, 1971b, 1971c; DeByle and Packer, 1972; Pierce et al., 1970, 1972; Brown, Gahler, and Marston, 1973; Tarrant, 1971). Yet, apart from nutrient losses calculated on the basis of removed timber products, there is little quantitative data on the effects of clearcut forest harvesting on the nutrient status of the forest ecosystem.

Previous studies in hardwood (Pierce, et al., 1970) and coniferous stands (Fredriksen, 1970; Gessel and Cole, 1965) have indicated that potentially significant losses of nutrients do occur when the forested areas are clearcut. The loss of nutrients from a clearcut forest, other than in the form of merchantable timber, might occur by: 1) the loss of particulate matter through erosion and surface transport in drainage water, 2) volatilization, and 3) transport of dissolved material in surface and subsurface drainage.

Streams draining forested areas typically are some of the least eutrophic of water sources (Cooper, 1969). Many forested watersheds serve as catchments for municipal water supplies. Headwater streams in the Rocky Mountain area are characteristically infertile as regards plant growth. Accelerated addition of nutrients to these streams from clearcut areas could alter their water quality and trophic structure.

Besides additions to streams through dissolved and particulate material from the watershed, leaching of slash deposited in the stream channel during harvesting could add significant amounts of nutrients.

Essentially no information is available on the impacts of clearcutting on nutrient compartments in forest stands of the Rocky Mountains and we are unaware of any published investigations on water quality as affected by clearcutting lodgepole pine forests. This manuscript reports a study of selected chemical properties of soils, logging residue, vegetation and subsurface water. It is hoped that this study on the effects of clearcutting on distribution of nutrients and biomass, and the loss of nutrients in subsurface water flow, will provide a better understanding of the possible consequences of this harvest practice in lodgepole pine forests.

REVIEW OF LITERATURE

Interest in nutrient cycling and losses in forests is not new. Historically, concern grew out of the European agricultural practice of removing forest tree litter for use as cattle bedding. Prior to 1900, there was study of the amounts of nutrients removed in wood from intensively harvested forests in France and Germany. On very shallow and nutrient-poor soils it was found that even small amounts of timber removal during several rotations seriously affected nutrient availability for tree growth (Rennie, 1955; Ovington, 1962). Interest in nutrient cycling in forests in the United States is relatively recent, however, with most major studies having begun no earlier than about ten years ago.

The influence of forest cutting on stream water chemistry has received much attention as a result of studies at the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire (Bormann et al., 1968; Likens, Bormann, and Johnson, 1969; Likens et al., 1970; Pierce et al., 1970, 1972). In the Hubbard Brook study, experimental clearcutting of a 39-acre watershed in 1965 followed by herbicide applications for three years to prevent regrowth greatly increased concentrations of most nutrients in the outflow stream, as compared with a nearby undisturbed watershed. Results from the Hubbard Brook study have stimulated interest in the effects of clearcutting on forest nutrients in other parts of the country, and by 1972, similar

investigations were being conducted in at least ten other experimental forests in the United States. The experimental design and results of these studies have been extensively reviewed in other publications (U. S. Forest Service, 1971a;Subcommittee on Public Lands, 1971, 1972; American Forest Institute, 1971; Report of the President's Advisory Panel on Timber and the Environment, 1973), and will not be reiterated here. Instead, it is intended to review pertinent literature concerned with nutrient and biomass dynamics in the components of soils, forest floor, and vegetation following clearcutting.

Forest Soil Nutrients

A discussion of clearcutting effects on forest soil nutrients should consider several processes by which the nutrient content of soils can be changed after forest harvesting. These processes include the nature and magnitude of element movement through soil horizons, the role of anion components of the soil solution in cation leaching, losses of dissolved nutrients in sediment and surface runoff, storage of nutrients in the organic layers of soils, and soil nutrient depletion resulting from export of forest crops from clearcut sites. Elemental inputs through mineralogical weathering and precipitation are also important as sources of nutrient recharge to forest soils.

Various studies have dealt with impacts of clearcutting on soils in forests other than lodgepole pine. Cole and Gessel (1965) conducted a study on soil leachates in a 31-year-old, 60 feet (18 meters) high Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco.*)* stand in Washington, originally planted on a gravelly (50-80 percent) soil after

logging and repeated burning. Tension lysimeter plates were placed at one- and 36-inch (2.5- and 91.4-cm) depths to sample leachates from the soil volume above. Clearcutting accelerated elemental release from the forest floor and mineral soil in this study. Of the nutrients released, 175 percent more nitrogen (N), 175 percent more phosphorus (P), 117 percent more potassium (K), and 78 percent more calcium (Ca) passed from the forest floor to the one inch soil depth in the clearcut site as compared to the control (undisturbed) forest site, for the 10-month period of measurement. These initial releases represented a reduction of 4.8 percent of the total N in the forest floor, and reductions of 7.7, 41.8, and 13.8 percent of the total P, K, and Ca in the forest floor, respectively. Due to the relatively low amounts of K in the forest floor, the authors reported that the release of K represented a large reduction in the total K capital in the forest floor.

Removal of trees also affected the elemental movement deeper in the soil profile. Of the nutrients released beneath the rooting zone (to the 36 inch depth), 81 percent more N, 233 percent more P, 17 percent more K, and 115 percent more Ca were removed beyond the effective rooting depth as compared with the control.

This element movement, both from the forest floor and at the lower soil depth, was characteristically high during the fall and early winter period (October through February), roughly paralleling the total monthly precipitation pattern in the study area. These leaching losses might be related to the high porosity and low exchange capacity of the soils. The authors also propose that the anion component of the soil

solution may play a controlling role in regulating cation leaching in these forest soils.

McColl and Cole (1968) used soil sampled from the B horizon from this same Douglas-fir plantation in Washington in laboratory experiments to determine the role of the bicarbonate ion on the leaching of cations from the soil exchange complex. They found a close relationship between the level of dissolved carbon dioxide and the level of cations in the soil solution, and concluded that hydrogen ions associated with the mobile bicarbonate ions in solution presumably replaced cations that move into solution from the soil exchange complex. Other studies have also indicated that the cation transport in many acid forest soils of the temperate region may be related to the level of dissolved carbon dioxide in the soil solution, which originates primarily from root respiration, decomposition of organic matter, and from the atmosphere (Remezov, 1958, 1961; Shilova, 1959; Remezov et al., 1964).

In addition to respiration, there are other sources of mobile anions. Clearcutting has been found to stimulate increases in cation leaching by increasing the rate of nitrification (Bormann, et al., 1968; Likens et al., 1969; Likens et al., 1970). It has been stated that at low pH levels nitrification proceeds slowly even in the presence of an adequate supply of substrate, and nitrifying bacteria may even be totally absent (Alexander, 1961; Jackson, 1967; Remezov and Pogrebnyak, 1969; Gigon and Rorison, 1972). However, Likens et al. (1969) found increased biological nitrification seemed to be the principal factor in producing acceleration in nutrient loss in drainage water from the

clearcut watershed at Hubbard Brook. The pH of the stream water from the cutover watershed decreased from 5.1 to 4.3 after cutting. In addition, populations of the nitrifying bacteria *Nitrosomonas* and *Nitrobacter* increased 18-fold and 34-fold, respectively, following clearcutting (Smith, Bormann, and Likens, 1968). Bormann et al. (1968) found that in the absence of vegetation, the microflora of the clear-cut watershed oxidized ammonia to nitrate rapidly. The end products of nitrification were important in terms of nutrient losses from the ecosystem, since increased amounts of hydrogen ions replaced cations on the humic-clay ion exchange complexes of the soil. Thus cations such as K and Ca were more quickly dissolved and leached from the ecosystem. The predominant source for the surplus cations was the breakdown of humic substances from the upper soil layers.

Chloride, sulfate, and phosphate are other anions which may occur in measurable quantities in the soil solution, but are generally low in acid forest soils (Wiklander, 1958; Hem, 1970). Likens et al. (1969) found that the normal release of sulfate by chemical weathering and microbial activity became negligible subsequent to clearcutting in Hubbard Brook. They attributed this reduction in sulfate production to decreased oxidation of various sulfur compounds by sulfur-oxidizing bacteria, since high concentrations of nitrate may be toxic to these organisms. An alternative explanation for decrease in sulfate production suggested by the authors was sulfate reduction induced by more widespread anaerobic conditions.

Dissolved nutrients in sediment and surface runoff is another potential mechanism for elemental loss following clearcutting. DeByle

and Packer (1972), in a small plot study of 65, 10- to 58-acre units in the northern Rocky Mountains of western Montana, found the combined losses of nutrients measured in both runoff and sediment, on slopes ranging from nine to 76 percent, were relatively high the first year after cutting and burning. The study was conducted on two sites ranging in elevation from 4200 feet (1280 meters) to 5400 feet (1646 meters). One site (Newman Ridge) was forested with lodgepole pine mixed with larger amounts of Douglas fir and western larch *(Larix occidentalis* Nutt.*)*. Only two years of data were available from this site, while four years of data were reported from the other site (Miller Creek), which was a mixture of western larch, Douglas-fir, and Engelmann spruce *(Picea engelmannii* (Parry) Engelm.*)*. However, the magnitude of losses and relative ranking of individual nutrients were the same for both sites.

DeByle and Packer (1972) found the nutrient losses in sediment and surface runoff decreased rapidly over time in the logged and burned plots, and may assume preburn levels within several years. From the plots on Miller Creek, 42 percent of the loss of nutrients was dissolved in surface runoff water. Five percent of the P, 62 percent of the K, and 35 percent of the Ca were so dissolved. The relative order of these nutrients was the same for Newman Ridge. Of the elements analyzed for, Ca predominated in the sediment in both sites, with lesser amounts of N, P, and K lost. Thus, K losses were particularly great in the dissolved form when compared to their relative ranking in the sediment. Losses of P in both runoff and sediment were negligible, but Ca was an important component in both runoff and sediment. In relation to the total amounts of these nutrients in a

foot-deep (30.5 cm) layer of soil, total nutrient losses for four years due to clearcutting and burning at Miller Creek in both runoff and sediment represented 0.5 percent of the P, 1.1 percent of the K, and 0.6 percent of the Ca. The authors calculated that it would take 50 forest rotations using similar logging and burning treatments to fully deplete the soils of these nutrients, not including additions from inputs in precipitation, mineral weathering, or decomposition of litter. The authors also speculated that K and Ca would probably be readily retained on the exchange complex in these acid soils when carried downward in percolating water, and would not be lost by deep seepage. Nitrification rates in several soil samples from Miller Creek were barely detectable, and nitrates were not present in large amounts at any time. They concluded that the portion of the plant nutrient supply lost in the overland flow probably represented the major portion of the dissolved nutrient losses from these two sites.

Sizeable amounts of nutrients can be removed from a forest ecosystem as a result of timber harvesting and subsequent removal of the merchantable timber. Cole, Gessel, and Dice (1968) reported the distribution and transfer of nutrients in a 36-year-old, second-growth, Douglas-fir plantation in western Washington. They found that the total vegetation (including subordinate vegetation, but predominantly the trees) accounted for 10 percent of the total N, two percent of the total P, 46 percent of the exchangeable K, and 28 percent of the exchangeable Ca. Exchangeable cations are often referred to as "available" cations or those cations which are extracted with a solution during the soil test (Jackson, 1958). They are considered to

be in a condition suitable for immediate uptake by plants. When inputs of nutrients to the ecosystem by precipitation, stem flow, leaf wash, and litter fall were considered, estimated finite supplies from the soil to the standing tree crop were 125 years for N, 582 years for P, 12 years for K, and 64 years for Ca. The authors concluded that the supply of K could become critical in a period considerably shorter than the life expectancy of the forest, but considered this possibility unlikely, due to addition of elements in ionic form through such processes as mineral solubility and organic matter mineralization. The authors also anticipated a change in the transfer rate between components of the ecosystem with time, such as that reported by Switzer, Nelson, and Smith (1966); the latter found that average annual N accumulation of loblolly pine *(Pinus taeda* L.*)* on a poor site during the second 30 years of growth was only 30 percent of the N retained during the first 30 years of development.

Based on the data of Cole et al. (1968), Curry (1973) stated that export of tree boles in excess of 20 percent of the total boles would represent a net loss of requisite availability of K, and concluded that much more study is needed to determine the impact of log export on site productivity.

Gessel, Cole, and Turner (1973) estimated that if this same Douglas-fir forest were clearcut, about 3.8 percent of the total N pool of the site would be removed from the site as part of the merchantable crop (tree boles and bark). In addition, 0.5 percent of the total P, 19.5 percent of the total K, and 9.6 percent of the total Ca would be removed, ignoring inputs from mineral weathering and precipitation. A

considerable quantity of these nutrients would be deposited on the forest floor in foliage and branch materials, more than doubling the amounts of K and Ca contained in the forest floor. They stated that acceleration of decomposition of organic matter would result, due both to a change in microclimate as well as the addition of substrate, resulting in an increase in the level of nutrients in the ionic form. They concluded that there is little probability of a significant increase in ion loss through leaching, however, since there have been no reported examples of nitrates accumulating in forest soils in the Pacific Northwest, and that carbonic acid would remain mostly in the ionized form in these acid soils.

Boyle and Ek (1972) evaluated macronutrient removals by conventional and bole and branch harvesting systems in a mixed hardwoods site in north central Wisconsin. The study was conducted in a stand of 45- to 50-year-old mixed hardwoods consisting of trembling aspen *(Populus tremuloides* Michx.*)*, paper birch *(Betula papyrifera* Marsh.*)*, sugar maple *(Acer saccharum* Marsh.*)* and northern red oak *(Quercus rubra* L.*)*. Soils were silty with relatively high nutrient status compared with other Wisconsin forest soils. Results indicated that minimum soil reserves of total N and extractable P were 15 times greater than the amounts removed by a conventional harvest cut at the end of a 45-year rotation. When boles and tops (subsequent to leaf fall) were harvested, the quantities of nutrients removed from the site almost doubled. The amount of total N removed by a bole and branch harvest represented 11.5 percent of the total soil N, and the amount of P removed was 12.0 percent of extractable soil P. Elements which

appeared to be most rapidly depleted from available reserves in the study area were K and Ca. Amounts removed in the conventional harvest represented 32.5 percent of the soil reserves of extractable K, and 31.8 percent of the extractable Ca soil reserves. Harvesting tops as well as boles increased the amounts of these nutrients removed from the site to 57.8 percent of extractable soil K, and 58.4 percent of extractable soil Ca. The authors stated that soil reserves of extractable K and Ca are probably adequate for only two crops similar to that removed, and reserves of extractable P and of total N are probably adequate for five or more rotations. Quantities of nutrients removed would be increased, according to the authors, if harvesting had been done with leaves on the trees, and if removal of trees less than 12.7 centimeters (cm) diameter at breast height (d.b.h.) had occurred. It was concluded that nutrient depletion following clear-cutting and nearly complete utilization of trees would not be a serious problem on soils with weatherable minerals, if erosion was minimized and if vegetative regrowth on the site was rapid.

Boyle, Phillips, and Ek (1973) conducted a study of "whole tree" harvesting, in which boles, branches, twigs, and leaves were removed from the site. A 30-acre, 40-year old, aspen-mixed hardwood second-growth forest in Wisconsin was harvested to remove all above-ground portions of trees larger than one or two inches (2.5 or 5.0 cm) in stem diameter. The total harvest represented a 108 percent weight increase over an expected standard bolewood harvest.

Output of nutrients in whole tree harvesting was 193 kilograms per hectare (kg/ha) of nitrate- and ammonium-nitrogen, 27 kg/ha of

extractable P, 130 kg/ha of extractable K, and 482 kg/ha of extractable Ca.

It was found that the amount of nitrate- and ammonium-N removed in a single whole tree harvest (193 kg/ha) would be supplied by a reserve in the top six inches (15.2 cm) of soil (27 kg/ha), plus inputs from precipitation in the next 30 years (168 kg/ha) and from mineralization of organic N (545 kg/ha). Mineralization of the 2134 kg/ha of organic N present in the soil was estimated to occur at a rate of one percent per year. N-fixation, denitrification, and erosional and leaching losses of N appeared to be minimal in these level soils when rapid revegetation followed cutting.

Boyle, Phillips, and Ek (1973) also estimated inputs of extractable P over the next 30 years to be 10 kg/ha from precipitation, and 30 kg/ha from mineralization and weathering. There were 114 kg/ha of extractable P in the soil. A weathering rate for release of P at less than 1 kg/ha/year, when added to precipitation inputs, balanced the tree crop requirement of 27 kg/ha.

Inputs of extractable K were estimated at 75 kg/ha from precipitation over the next 30 years, and 120 kg/ha from mineralization and weathering (assuming a weathering rate of 4.0 kg/ha/year). Amounts in the soil were 129 kg/ha. Thus the total needs of the tree crop (130 kg/ha) could be met by additions from weathering and precipitation.

Ca appeared to be potentially limiting when the amount removed in harvest (428 kg/ha) was compared to soil reserves (657 kg/ha) and inputs from precipitation (120 kg/ha) and mineralization and weathering (240 kg/ha). Weathering production of extractable Ca was estimated at 8.0 kg/ha/year.

The authors concluded that supplies of Ca might begin to limit growth rates and biomass after nine tree crop rotations (270 years). It was suggested that nutrient removals could be reduced by harvesting trees after leaf fall (as in Boyle and Ek, 1972). They also stated that the plant available nutrient reserves in these soils were probably conservative estimates of the amounts of these nutrients available to tree roots, since they included only the top six inches of soil, and root systems actually penetrated to a three foot depth (91.4 cm). Thus, supplements of Ca from roots deeper than six inches were expected to extend the rotation estimate for depletion. In addition, lime applications were suggested as a measure to offset potential Ca deficiencies.

As early as 1949 there were questions concerning site deterioration following clearcutting in lodgepole pine forests in the Rocky Mountains. Trimble and Tripp (1949) observed conditions in many of the soil types found in lodgepole pine in northern Wyoming and southern Montana at elevations between 7000 feet (2134 meters) and 9000 feet (2743 meters). They found in many old-growth stands (ca. 200 years old) where 25 to 50 percent of the volume had been removed 20 to 35 years previous, that bare subsoil was still evident in areas of haul roads and skid trails, resulting from erosion, which still was continuing. In addition, areas between the trails showed thin needle and humus layers of the forest floor, and dry and compacted soil resulting from the sealing and baking effects of increased radiation and precipitation. In some areas nearly all the organic matter was gone from the surface, and the little humus present appeared blackened and

charred as a result of accelerated oxidation. They concluded that it took 30 to 40 years after establishment of the stand following clearcutting before any appreciable litter and humus layers began to form. A stand was 100 years old before a forest floor developed of one to two inches (2.5 to 5.0 cm) thick. Stands that were over 200 years old were found to have a forest floor ranging in depth from three to six inches (7.6 to 15.2 cm).

Five publications which directly pertain to soil nutrients in lodgepole pine forests will be reviewed here. Woodmansee (1972) developed a potassium model to simulate a standard clearcutting practice in a 70-year old lodgepole pine forest, in which boles were removed from the forest and the slash (branches, needles, and cones) was left at the site as litter to be decomposed at accelerated rates (due to a more favorable microclimate resulting from cutting). According to the simulation model, nutrients would be released to the uppermost mineral soil horizon, and the roots would become soil organic matter with their nutrients released to the mineral soil. Erosion would occur, but at reduced rates due to soil stabilization caused by the logging residues. Leaching would occur at accelerated rates for about six years because of nutrient release from slash and dead roots. At the end of three harvest cuttings at 70-year intervals, the ecosystem would have lost about 15 to 20 percent of its K capital. Each successive clearcutting cycle would yield smaller amounts of biomass in the individual ecosystem components, and a consequently smaller total plant biomass would result. Woodmansee (1972) concluded that certain clearcutting practices (e.g., bole removal and complete

removal of logging residues by burning) could result in drastically reduced nutrient pools, and an consequent reduction in tree biomass production.

Zinke and Colwell (1972) found that if only tree stems were removed in a harvest cutting of a lodgepole pine forest, only two to five percent of the nutrients (N, P, Ca, Mg, and K) were lost, and that needles, branches, and roots left to decompose would return to the soil as additional nutrient storage compartments. The authors studied the uptake and storage of nutrients in a 100-year-old lodgepole pine forest in northern California to determine the distribution and variations of these nutrients in needles, branches, wood, bark, and roots of the trees, and in the associated litter and mineral soil. The proportions of nutrients (g/m^2) stored in the soil were generally larger than those in the tree and litter, except for P, which was highest in litter. The authors stressed the importance of maintaining adequate storage of available nutrients in forest soils.

Moir and Grier (1969) reported tabular data for loss-on-ignition, mineral and ash content, and for N, P, K, and Ca content of four forest floor humus horizons in eight lodgepole pine stands of variable density and productivity. With one or possibly two exceptions, the lodgepole pine stands studied were typical for the species. The stands were dense (ranging from 1730 stems/ha in a thinned stand, to 35,088 stems/ha) and even-aged (ranging from 60 to 98 years). The stands ranged in elevation from 2500 to 2575 meters in gentle upland topography along the eastern slopes of the Rocky Mountains in Colorado. The exceptions included a stand which was uniformly and heavily thinned about 35 years

ago, and a stand at a higher elevation (2775 meters) on a moderate slope (27 percent) in the Engelmann spruce-subalpine fir zone (*Abies lasiocarpa* (Hook.) Nutt.) (Daubenmire, 1943).

The ground flora cover was less than five percent, with the result that the forest litter and subsequent humus were essentially derived from lodgepole pine trees. The organic layers formed a thin (two to three cm) continuous mat. The surface litter layer (L horizon) consisted of lodgepole pine needles, twigs, cones, and bark flakes, and represented a two- to three-year accumulation of litter. The F1 and F2 horizons consisted of pine debris in various stages of fragmentation, decomposition, and compaction. The dark, wavy A1 or A11 horizon was an intimate mixture of humus and mineral particles, and was about 0.5 cm thick. The four horizons were considered to form an amphimorphic forest humus.

Mean total N values were 91, 154, 87, and 80 kg/ha for the L, F1, F2, and A1 or A11 horizons respectively, for a total of 412 kg/ha. These authors found a trend of increasing N percent with increasing litter decomposition (L, 0.82 percent; F1, 1.32 percent; F2, 1.40 percent; and A1 or A11, 1.54 percent). About 60 percent of the total forest floor N was in the L and F1 horizons, where the greatest organic accumulation occurs.

Moir and Grier's (1969) reported values for determinations of P, K, and Ca represented total quantities, including both the organic- and mineral-bound elements which are potentially mobile through exchange or decomposition. Total P of the forest floor was 38 kg/ha. There was evidence of P leaching from the litter and retention in the

A1 or A11 horizon. The trend was for an increase in percent P at successively lower horizons (L, 0.06 percent; F1, 0.10 percent; F2, 0.12 percent; and A1 or A11, 0.27 percent), and about one-third (12 kg/ha) of the total P was in the A1 or A11 horizon.

Total K in these humus horizons was 110 kg/ha, and increased in successively lower forest floor horizons (L, 0.13 percent K; F1, 0.24 percent; F2, 0.36 percent; and A1 or A11, 1.05 percent). Forty-five percent of the total K (49 kg/ha) was in the A1 or A11 horizon. The authors suggested that this K retention in the A1 or A11 horizon may be caused by the high cation exchange capacity (C.E.C.) of this horizon in relation to underlying mineral soil, or by the abundance of microorganisms in this horizon, with both mechanisms operating to provide an effective barrier against K leaching to lower soil depths.

Total Ca of the forest floor was 150 kg/ha, and 60 percent (96 kg/ha) of this Ca was in the L and F1 horizons. Concentrations were nearly the same in each horizon (L, 0.5 percent Ca; F1, 0.4 percent; F2, 0.4 percent; and A1 or A11, 0.6 percent) which indicated that Ca appeared to be less mobile than P or K.

Woodmansee (1972) carried the work of Moir and Grier (1969) further by reporting certain chemical properties of mineral soils in one of the eight lodgepole pine stands mentioned earlier. This stand is located on an upland, east-facing slope of eight percent at an elevation of 2690 meters. The vegetation is even-aged, closed-canopied lodgepole pine with a density of 8896 stems/ha. Chemical data indicated surface mineral horizons were very acid (pH 4.8 to 5.2), and increased in pH to medium acid (pH 5.6 to 5.8) with increasing depth. Total N decreased

with depth, from 0.087 to 0.014 percent. There appeared to be no readily discernible trend of available P levels, which ranged from 12.5 to 42.5 parts per million (ppm), but it appeared that profiles which contained a clay accumulation in a subsurface horizon also had a P accumulation in that horizon.

Exchangeable K showed no clearly discernible pattern of distribution, while C.E.C. values appeared to correlate with zones of accumulation of clay and humus colloids. Exchangeable K ranged from 0.14 to 0.53 milliequivalents per 100 grams of soil (meq/100 g), and C.E.C. ranged from 9.4 to 24.2 meq/100 g. Exchangeable Ca ranged from 2.31 to 9.98 meq/100 g, and showed no consistent trend with depth.

Daubenmire (1953) reported the nutrient content of needle litter of coniferous trees in the northern Rocky Mountains. He found that litter from different species varied considerably in nutrient composition. Litter from lodgepole pine had slightly above average total N content (0.59 percent) as compared with litter from the other 11 tree species. Values for percent total P and K in lodgepole pine needles, however, were the lowest of any of the litter types examined (0.04 and 0.20 percent, respectively). Needle litter content of Ca was relatively low (0.64) compared to litter from the other species. Data such as these may have value in evaluating species influences upon soil by the nature of litter produced, according to the author.

The remaining publication related to lodgepole pine forest soil nutrients is that of Stottlemyer and Ralston (1970). They reported the storage of nutrients in organic horizons of soils in a lodgepole pine stand in the Fraser Experimental Forest in western Colorado. They were

particularly interested in forest floor nutrient budgets since these nutrient storage fractions can be altered drastically by forest harvesting.

The authors found a large forest floor biomass (28,590 kg/ha), which indicated a slow cycling rate of these organic materials. Amounts of total K in the litter horizon (L), fermentation zone (F), and humus layer (H) of the forest floor were 2.7, 3.8, and 16.5 kg/ha respectively. The H horizon accounted for 72 percent of the total K in these organic horizons. Estimates of weights of this cation primarily reflected differences in the total weight of the organic layers; the H horizon represented 59 percent of the total forest floor biomass (16,810 kg/ha), while the L and F horizons were 17 and 24 percent, respectively. Concentrations of K increased with depth, which indicated a high mobility and subsequent leaching of K to the lower zone. K accumulation was greatest in the more highly colloidal humus horizon.

Total Ca, however, was more evenly distributed throughout all layers, which indicated that this cation was probably not as readily removed by leaching. Amounts of total Ca in the L, F, and H horizons were 25.1, 35.0, 85.8 kg/ha, respectively.

In summary, the available literature concerning impacts of clear-cutting on forest soil nutrients indicate that removing the trees during forest harvesting causes a marked redistribution of the nutrients in a forest ecosystem. The cycle of nutrients between the forest and soil system is temporarily halted by cutting and removing the trees. The degree to which the nutrient cycling process is disrupted depends

on many factors, including soil characteristics, degree of vegetation removal, and soil microorganisms. In addition, various nutrients are affected differently by the cutting treatments, due to different physiochemical properties, and rates and specific pathways of transfer. For example, N and Ca are bound chemically within biological tissue so that processes of decomposition must precede leaching and transport of these elements. K, on the other hand, remains in a soluble form within the plant, and consequently its transfer is regulated primarily by water movement and the presence of exchange sites.

Removal of trees represents a break in the nutrient cycle between the soil and the tree system, but studies indicate that the tree bole component may not represent the most predominant path of the nutrient cycle. In standard clearcutting operations the nutrients in the foliage, twigs, branches, and roots are returned to the soil for decomposition and subsequent release. The ultimate fate of these nutrients (e.g., leaching through soil horizons to lower depths or ultimately into groundwater, losses in surface runoff, incorporation into the biomass of developing vegetation, etc.) is related to the complex interaction of many factors, including soil exchange capacity, porosity, pH, and microflora populations, potential for erosion, and extent of revegetation following clearcutting.

Revegetation and Nutrients

Revegetation following clearcutting has important implications in nutrient cycling. Rapid growth of successional species may tend to reduce nutrient losses through incorporation into the developing biomass

of nutrients that become available and that otherwise might be lost from the cutover ecosystem. Thus this incorporation of nutrients by successional species would move the ecosystem back toward the stable, steady-state pattern of nutrient circulation characteristic of the mature, uncut forest.

Marks and Bormann (1972) found very dense stands of pin cherry *(Prunus pennsylvanica* L.*)* developed rapidly on the clearcut watershed at Hubbard Brook when herbicide applications were discontinued. They measured the rate of biomass and nutrient accumulation in the tissues of this tree species in different stages of recovery (one, four, six, and 14 years after clearcutting), and found a full canopy was established within four years. Incorporation of nutrient elements into the developing biomass was also rapid, particularly for N and Ca. They reported annual uptake of N in the four- and six-year old stands to be 10.0 g/m^2 (100 kg/ha), or about 50 percent greater than uptake in the mature, undisturbed ecosystem (6.5 g/m^2 or 65 kg/ha). The authors concluded that these high rates of nutrient uptake and biomass accumulation resulted from the adaptive capacity of this species to utilize the greater availability of nutrients and water on the clearcut site.

Relatively little work has been done on the vegetational changes during secondary succession following clearcutting in lodgepole pine forests in the Rocky Mountains. A notable exception is the study of Basile and Jensen (1971) in Montana. Twenty-five clearcut- and burned-sites at elevations below 7500 feet (2286 meters) were selected to represent a range in post-clearcut ages of from two to 17 years after cutting. Total understory production reached its peak about 11

years after clearcutting, but the several vegetational classes performed differently with respect to time.

Grass production peaked at about 13 years, while sedges showed no discernible pattern. Forb production peaked at 10 years. Shrub production increased over the entire range of time, but appeared to begin leveling off at 15 or 16 years after clearcutting. The authors attributed the concurrent increase in shrub production and decrease in herbaceous plants to grouse whortleberry *(Vaccinium scoparium* Leiberg*)* which accounted for one-half of the shrub cover on these sites. Since the roots of this species occurred mostly within two or three inches (5 or 7.5 cm) of the soil surface, it was thought to have a competitive advantage for exploitation of the moisture resulting from light summer rains.

Tree regeneration was found to affect understory vegetation production through increasing competition for moisture and light. It appeared that lodgepole pine adversely affected herbaceous plants while still in the seedling stage. Herbage biomass started to decline on 10- and 11-year old clearcuts where tree heights averaged only two feet (61 cm). Again it was speculated by the authors that the lodgepole pine seedlings had a competitive advantage over herbaceous plants for soil moisture, due to the development of extensive root systems by 10 years of age.

Multiple regression analysis was used by Basile and Jensen (1971) to determine combinations of environmental factors that substantially affect understory vegetation biomass. It was found that available K in the soil solum ranked second to the field capacity and wilting

point variables in degree of correlation with understory production. Contributions of other soil chemical variables (e.g., total N, pH) to the model were negligible. In a later study, Basile (1971) tested site index as a possible indicator of potential for herbaceous vegetation production following clearcutting, and found this measure of site potential for tree growth accounts for only one percent of the variation in production.

There is disagreement in the literature concerning the response of understory vegetation to clearcutting in lodgepole pine forests. Trappe (1959) found that *V. scoparium*, a major species in lodgepole pine stands in north-eastern Oregon, almost entirely disappeared from clearcuts, and survived only where sheltered by slash or residual trees. In general, shrubs decreased and forbs increased. Vogl and Ryder (1969), however, found *V. scoparium* was little affected by clearcutting and burning in a mixed conifer forest of Engelmann spruce, subalpine fir, western larch, and lodgepole pine, in northwestern Montana. Herb, moss, and liverwort cover was greater in the burned than in the unburned locations, but shrubs decreased. The fertility assay showed larger amounts of nutrient minerals in the burned soils, with 37 percent more total N, 18 percent more extractable P, 26 percent more extractable K, and more than twice as much extractable Ca.

Observations were made on 99 Engelmann spruce-subalpine fir clearcutting units in Colorado by Alexander (1966), who found that ground vegetation (principally *V. scoparium*) was little altered by cutting. It was found that medium to heavy density of ground vegetation was beneficial to both spruce and fir stocking, possibly due to an

improvement in microenvironment caused by shading and mulching. Another study by Alexander (1968) in the Fraser Experimental Forest in Colorado indicated that ground vegetation on north- and northwest-facing slopes at 10,500 feet (3200 meters) to 11,000 feet (3353 meters) was predominantly *V. scoparium*, and this species did not increase after cutting. However, considerable increase in ground vegetation occurred after clearcutting in bogs and wet places, which consisted primarily of grasses, sedges, and other herbaceous plants. Grasses and other ground vegetation increased so rapidly in these wet sites following cutting as to provide an effective barrier to tree reproduction establishment, resulting in a decrease in numbers of seedlings and saplings as compared to numbers prior to clearcutting. Lotan and Dahlgreen (1971) also found competition of ground vegetation with lodgepole pine seedlings in the *Abies lasiocarpa/V. scoparium* habitat type in western Wyoming at an elevation of 7900 feet (2408 meters). They attributed lodgepole pine seedling mortality to soil-moisture depletion caused by competing vegetation.

Stahelin (1943) studied the rate of restocking on eight burned-over areas ranging from 9000 to 11,000 feet (2743 to 3353 meters) in the Engelmann spruce-subalpine fir type in the central Rocky Mountains of northern Colorado and southern Wyoming. He found coniferous reproduction within the distribution of lodgepole pine to be consistently better on plots with a *Vaccinium* spp. cover than on plots with grass cover. He assumed *Vaccinium* spp. did not prevent seeds from reaching mineral soil to the same extent as a cover of sod-forming herbaceous vegetation, and it was less competitive with tree seedlings

for water and nutrients. Within the distribution of lodgepole pine, 39 percent of the milacres sampled had been restocked with coniferous seedlings since fires that had occurred between 50 and 70 years ago. Two-thirds of the plots within the lodgepole pine zone were located in granitic soil with a high gravel content. The author concluded that coniferous restocking appeared to be related to soil porosity and clay content, as well as type of vegetation occurring on the sites.

Although good stocking of lodgepole pine regeneration following clearcutting usually occurs in the central Rocky Mountains (Alexander, 1966b), several studies on tree reproduction on lodgepole pine clearcut sites have concluded that stocking of lodgepole pine seedlings is better on disturbed mineral seedbeds as compared with undisturbed litter soils. Alexander (1966a) studied a clearcut lodgepole pine stand in the Medicine Bow National Forest in Wyoming, and found a lower density of lodgepole pine seedlings on undisturbed seedbeds in relation to disturbed mineral soil seedbeds. Because lodgepole pine seed was not dispersed more than 200 feet (61 meters) from standing trees, most seed for regeneration came from cones left in the slash. Lodgepole pine slash in this area had a high proportion of serotinous cones, which released most of their seeds the first year after clearcutting.

Johnson (1968) found regeneration on a pre-scarified soil in an 85-year old stand of lodgepole pine in the lower foothills of Alberta exceeded 80 percent stocking. Height growth of the tallest lodgepole pine seedlings on scarified areas was over 50 percent greater than those on undisturbed areas. Most of the seedlings present originated

during the first two years after logging, and the important seed source was from the slash-borne cones, with the seed supply from stands bordering the clearcut minimal.

Trappe (1959) reported almost twice as many lodgepole pine seedlings grew on mineral soil as on undistrubed litter following clearcutting in the Blue Mountains of north-eastern Oregon, and the majority of seedlings were established in the open rather than under slash accumulations.

The only literature related to lodgepole pine-soil relationships concerned the lodgepole pine forests in the Pacific Northwest (Stephens, 1966; Youngberg and Dahms, 1970). That information which would apply to the Rocky Mountains indicated that lodgepole pine grew only on well- and excessively well-drained, sandy soils of low fertility, or on poorly and very poorly drained, highly organic soils, and was unable to compete with associated conifers on medium or moderately fine texture soils in the northwest Cascade Mountains of Oregon. Lodgepole pine appeared to form an "edaphic climax" on droughty soils of low fertility. This condition is well recognized in the central Rocky Mountains.

Nutrient Requirements of Species

One of the factors that may be of importance in revegetation is the nutritional regime under which plants are growing in clearcut sites and their metabolic requirements for certain nutrients. Studies have been conducted to determine nutrient requirements of at least two species commonly found in lodgepole pine forests in the Rocky Mountains.

Ingestad (1973) investigated the mineral nutrient requirements of *Vaccinium myrtillus* L., the dwarf shrub which was found in Moir's (1969) lodgepole pine stands in Colorado, and is closely related in habitat to *V. scoparium*, the predominant understory species in my stands. He describes this species as:

> characteristic members of the plant community in the conifer forests of the boreal zone. . . they come from an extreme nutritional environment characterized by leached soils with low pH, low base saturation and low lime content. The nutrient turnover is slow, and the amounts of available nutrients are small.

Plants were grown in nutrient solutions, and N, P, K, and Ca were studied in detail to investigate the nutrient requirements for maximum growth. The growth rate and the relative internal content of K were affected very little by changes in the relative external K concentration. Ca, on the other hand, was removed from the solution down to low concentrations by a high uptake rate, resulting in high relative internal contents. The high uptake of Ca appeared to be luxury consumption, as there was no corresponding increase in growth rate.

There was uptake of both the N sources ammonium and nitrate, but when both were present, ammonium uptake was much more rapid than nitrate uptake. Calcium was taken up in conjunction with nitrate when the latter was the sole N source, and phosphate with ammonium. Good growth of *V. myrtillus* occurred with ammonium as the sole N source.

The author associated the low requirement for K with the xeromorphic character of *V. myrtillus*, and less need of K for control of the water balance. The capacity for high Ca uptake may relate to the ability of this species to grow in acidic soils with low Ca availability, which has been observed with other ericaceous plants (calcifuges).

Etter (1969) grew lodgepole pine seedlings for six weeks using nutrient solutions containing 0.4, 4.0, or 8.0 meq/liter nitrate-N, and found increased nitrate supply resulted in a decrease in drought resistance. This may be significant in light of the small quantities of nitrates usually found in acid forest soils (Alexander, 1961; Boyle and Ek, 1972; DeByle and Packer, 1972; Gessel et al., 1973). Remezov and Pegrebnyak (1969) stated that pine forest soils contained only very small amounts of nitrates, and that nitrifying microorganisms were not detected in the soil. Improvement cutting resulted in only a slight increase in soil nitrates in some stands, and in one case the soil had no nitrification capacity, and none was induced by improvement cutting. Pine trees developed exclusively in an environment of ammonium nutrition, and ammonification capacity of the soil increased after improvement cutting.

Cochran (1972) grew lodgepole and ponderosa pine *(Pinus ponderosa* Laws.) under nine different temperature regimes and four levels of soil fertility to investigate growth rates of the two species in south-central Oregon. Fertilization increased growth of both species under all temperature regimes studied, but there was no consistent difference in species response, which indicated that lodgepole pine was not less "nutrient demanding" than ponderosa pine in the first four months of development.

Forest Biomass

Basic to the determination of nutrient quantities in various components of the ecosystem is the determination of dry matter production.

Accurate estimates of forest biomass and its distribution are essential to the understanding of clearcutting effects on nutrients in vegetational components of the forest ecosystem.

Most work dealing with productivity of forest ecosystems has been concerned with the economically valuable volume of timber, ignoring such components as the leaves and branches. For example, stem growth and yield information is available for lodgepole pine in the Colorado Rocky Mountains (Myers, 1964, 1967, 1969; Cole, 1971) and in other areas (Youngberg and Dahms, 1970; Cole and Stage, 1972; Dahms, 1971, 1973). Site index is another measure of tree stem growth, and has been reported for lodgepole pine by Alexander (1966c), Dahms (1966), and Alexander, Tackle, and Dahms (1967).

Allometric methods for determination of total forest tree biomass have been applied to a wide range of forests, from uniform single species plantations (Forrest and Ovington, 1970) to tropical rain forests (Hozumi et al., 1969). This procedure involves calculation of regression equations from a range of sample trees selected from a stand, based on determination of relationships between some easily obtainable measurement on a standing tree and its total biomass or biomass component. This regression estimation technique of tree biomass estimation has also been called "dimension analysis of woody plants" (Whittaker, 1961, 1965, 1966; Whittaker and Woodwell, 1968, 1969), and "allometry" (Kira and Shidei, 1967; Satoo, 1970).

The allometric method for determining forest tree biomass involves three phases (Art and Marks, 1971). Trees are recorded by species and d.b.h. (and often, height) on a quadrat basis. Using a certain number

of sample trees, difficultly measured allometric growth parameters (e.g., total stem, branch, or foliage biomass) are related by regression analysis to more easily measured parameters (ultimately to d.b.h.). The calculation of tree biomass per unit area by extrapolation from sample tree data is the third step. Because the different proportions of foliage branch, and trunk material in trees of different sizes, accurate estimation of the weight of tree stands requires a number of trees to be sampled, and these trees should be distributed over the range of tree sizes (Attiwell and Ovington, 1968). The accuracy and precision are determined by the parameters used. If d.b.h. is used, for example, a relatively good estimate of bole weight can be expected, but other components, especially those in which environmental factors have great influence (e.g., the mass of foliage or branches), may be highly variable (Ovington, Forrest, and Armstrong, 1967).

One method which has recently gained considerable popularity for determining stem dry weight of sample trees involves converting stem volumes to dry weight, by including the wood property of specific gravity in the calculation. Tree dry weights are then calculated by converting specific gravity to dry weight, and multiplying this factor by stem volume obtained from standard forestry mensurational procedures (Ovington, 1962; Will, 1964; Zobel, Roberds, and Ralston, 1969).

Collett (1963) determined specific gravities on 2666 cross sections from 444 lodgepole pine trees throughout the range of the species in Colorado and Wyoming. He found the average specific gravity of lodgepole pine was 0.395, and that the density of specimen wood from the

breast-height level in the bole of the tree was very close to that of the whole-tree estimate, and to the average of lodgepole pine wood. An analysis of variance showed that the most important single factor in explaining specific gravity variation in cross sections was the height level (vertical position) in the bole of the tree. Also interacting to affect specific gravity were the age and diameter of the specimen, and the height class of the tree from which specimens are taken. Regression analyses of whole-tree specific gravity with five independent variables and transformations indicated tree diameter as the most important single variable in explaining variation in this property. His overall average specific gravity of 0.395 compared to Tackle's (1962) value of 0.386 for lodgepole pine in the intermountain region.

Landis (1972) conducted a study to determine an allometric model for bole biomass estimates of Engelmann spruce and quaking aspen *(Populus tremuloides* Michx.*)* in the San Juan Mountains of southwestern Colorado. He found that stem biomass could be estimated using the linear regression between diameter at breast height squared times tree height (D^2H) and stem dry weight for either species, using this model alone, with a resultant correlation coefficient (r) of 0.993. He concluded that this all-species relationship was not surprising, since an allometric function is not necessarily specific to a single tree species, but may be common to species having similar life forms. Quaking aspen in his sites exhibited an excurrent form, with one main stem for the majority of the vertical plane, which was similar to the stem form of Engelmann spruce.

Several similar tree biomass studies have been conducted in lodgepole pine forests. Johnstone (1971) determined tree and component weights of 100-year-old lodgepole pine trees from three stands of different stocking densities in southwestern Alberta at an elevation of 4600 feet (1402 meters). Allometric relationships relating the independent variable D^2H to the dependent variables of bole, branch, and needle dry weight were presented, and estimates of the total standing crop were given. The author stated that caution should be exercised in comparing stand dry matter production where stocking density extremes are encountered in species such as lodgepole pine, where height growth of trees is influenced by extremes in stand density.

Moir (1972) presented tree harvest data from a 70-year-old naturally-thinned stand of lodgepole pine in the subalpine *P. contorta/ V. myrtillus* habitat, and from two stands of similar age in the drier *P. contorta/Geranium fremontii* habitat, on the east slopes of the Front Range of Colorado. Stem, bark, living branch, and foliage biomass were calculated using appropriate allometric equations. The more mesic site was found to be more productive than the other two, with a higher proportion of green needles to living shoot parts, although none of the lodgepole pine stands were very productive in terms of annual stem and branch production when compared with other species of young pine grown in plantations (Hatiya, Doi, and Kobayashi, 1965; Madgwick, 1968; Forrest, 1969). Organic production and turnover in the three stands were approximately steady, with new growth and branch mortality balanced by observed contributions of branches and needles to the litterfall.

The author suggested that the major limitation of lodgepole pine productivity in the central and northern Rocky Mountains may be the generally infertile soils and inimical continental climates. He stressed that management decisions in the Colorado lodgepole pine zone must recognize the inherent low productivity of the species, and that lodgepole pine stands in environments of site index of 90 or less should be regarded as only minor resources of wood harvest.

Measurements of foliage biomass and surface area in forest stands can be useful in nutrient cycling studies. Lopushinsky (1970) studied the relationship of needle surface area to needle volume in ponderosa and lodgepole pine. Moir and Francis (1972) reported foliage biomass and surface area from the three lodgepole pine stands reported in Moir (1972). In Moir and Francis' study, foliage biomass and surface area were strongly related to stand and site characteristics. It was found that mean fascicle weights were significantly affected by dominance, crown position, and fascicle age. Total oven dry foliage biomass for the thinned stand of low productivity was 0.49 kg/m^2, for another stand of low productivity foliage biomass was 0.84 kg/m^2, and for the more mesic stand of moderate productivity foliage biomass was 1.74 kg/m^2. The biomass ratio of 0.6:1.0:2.0 was in approximate proportion to the respective site indices of the three stands. The authors concluded that lodgepole pine stands in different environments and with different tree spacings should be interpreted individually in relation to components of variation of fascicle biomass.

Water Quality

Literature on the effects of forest management practices, principally clearcutting, on water quality has dealt mainly with physical alterations (sedimentation, temperature), water yields, and more recently with nutrient losses following cutting.

Increases in water yield from cut areas by reduction of transpiration and interception is well documented (Goodell, 1964; Hibbert, 1967; Kochenderfer and Patric, 1970; Kovener, 1957; Rothacher, 1970a). The major importance of increased water yields is the supplementation of stream flow during periods of normally low flow, i.e., summer and early fall (Goodell, 1959; Hoyt and Troxell, 1932; Kochenderfer and Patric, 1970; Reinhart and Eschner,1962; Rothacher, 1970b). Increases in base flows could be beneficial in providing increased living space for stream organisms (Chapman, 1962) and supplying needed water exchange in gravel beds for incubating fish eggs (Hall and Lantz, 1969; Pollard, 1955; Vaux, 1962).

Forest soils generally have high infiltration rates that reduce surface runoff and noticable erosion (Brown, 1972; Hewlett and Helvey, 1970). The physical act of felling all trees on a watershed is usually insufficient to cause significant increases in turbidity (Brown, 1972). The major cause of erosion from clearcut areas is the result of a decrease in the soil infiltration rate. Decreased infiltration may result from soil compaction during road construction and skidding (Burns, 1972; Hornbeck and Reinhart, 1964; Megahan and Kidd, 1972; Reinhart and Eschner, 1962), and from slash burning that destroys surface organic material causing a hydrophobic soil condition (Brown and Krygier, 1971; Fredriksen, 1970; Swanston, 1971). Logging too close to stream channels may cause bank disturbance and result in increased sedimentation. The effects of increased sedimentation on stream biota are well documented in a bibliography by Gibbons and Salo (1973).

Cutting riparian vegetation on small forested streams generally results in increased water temperatures (Levno and Rothacher, 1967; Meehan, et al., 1969) Brown and Krygier (1970) reported temperature data following clearcutting treatments on the Alsea Watershed in Oregon. On a patch cut watershed with 50 to 100 feet buffer strips along the stream channel, no temperature changes were attributed to the cutting practice. A second watershed was clearcut and later burned. Mean monthly maximum temperatures were increased by 14°F following this treatment and the annual maximum was increased by 28°F. It is apparent from this and similar studies that stream temperature increases need not be associated with cutting if the use of a buffer strip along the stream is employed to maintain protection from insolation. Buffer strips can also aid in reducing turbidity and deposition of slash in streams by keeping the logging operation away from the channel.

Early studies on nutrient fluxes in undisturbed forest watersheds revealed that the forest ecosystem lost very little of its nutrient reserves through leaching (Cole, et al.,1961, 1967; Likens, et al.,1967). An early study on clearcutting at the Cedar Creek watershed in western Washington (Gessel and Cole, 1965),followed nutrient movements through the soil profile on 0.2 acre plots with the use of tension lysimeters. Douglas-fir was removed from the plots by clearcutting and tension lysimeters were installed at depths of one and 36 inches. Clearcutting resulted in increased water yields and only slightly greater losses of nitrogen, potassium and calcium than were reported from the control site. Because of the greater volumes of water moving through the clearcut area, concentrations of the solutes in the soil-water were actually less than from the control area. Total nutrient losses were considered insignificant as they represented less than one percent of the total elements in the soil system.

Studies on nutrient cycling in forest systems began to receive increased attention following the dramatic results obtained from an experiment at the Hubbard Brook Experimental Forest in New Hampshire (Bormann, et al.,1967, 1968, 1969; Likens, et al.,1970; Pierce, et al.,1970). Treatment at Hubbard Brook consisted of felling all trees on a 39 acre watershed and leaving them lie. The area was subsequently treated with herbicide to prevent any regrowth. Results of this drastic treatment probably represents the maximum amounts of nutrients that could be lost from a forested area (Likens, et al., 1970).

Removal of vegetation resulted in a significant increase in stream-flow during the summer with differences during snowmelt periods restricted to changes in timing only (Pierce, et al., 1970).

Following removal of the vegetation, tremendous increases in nitrate concentrations in stream water were noted. Nitrate concentrations were about 56-times greater two years after cutting than from a control stream. Ammonium concentration during the same period showed a small decrease (Likens et al., 1970). In the first three years after cutting the loss of nitrate amounted to about 342 kg/ha (Pierce, et al., 1972). Of the total nitrogen lost, approximately 97 percent occurred as dissolved substances. Overall, 85 percent of all material lost occurred as dissolved substances (Bormann, et al., 1969).

Concentrations of other nutrients also increased following devegetation but less drastically than nitrate. Average stream concentrations for the second year following cutting showed cation losses were three to twenty times greater than from the uncut watershed. Concentration decreases were noted for sulfate, bicarbonate, and ammonia (Likens, et al., 1970).

A subsequent study at Hubbard Brook in which trees were harvested by standard clearcutting techniques resulted in similar trends in nutrient removal but losses were of lesser magnitude (Pierce, et al., 1972).

Likens, et al.(1969) theorized that the increase in nitrate in the stream was the result of increased nitrification in the humus layers of the clearcut area. Although the pH of the stream was very low (5.1 in 1965-66 and 4.3 in 1966-68), nitrate concentrations increased during this period along with increases in soil nitrifying bacteria.

Anion mobilization as a mechanism for nutrient removal was clearly demonstrated during the Hubbard Brook study, since the total equivalents of nitrate lost almost completely balanced the equivalents of cations released (Likens, et al., 1969). McColl and Cole (1968) have demonstrated that in other forest systems bicarbonate is important in cation movement.

Loss of nitrate from a clearcut oak-hickory and yellow poplar watershed at the Fernow Experimental Forest, W. Virginia, was about ten times greater than from a control watershed, but only about one-third as great as those reported at Hubbard Brook during the first year following clearcutting (U. S. Forest Service, 1971a).

The effects of four watershed treatments on nutrient losses were investigated at Coweeta Hydrologic Laboratory in North Carolina (Johnson and Swank, 1973). Treatments consisted of : 1) a mature hardwood forest; 2) a seven-year-old hardwood coppice that was clearcut and allowed to regrow without timber removal; 3) a 13-year-old white pine plantation; and 4) a weed field that had been fertilized several times. The weed-to-forest succession treatment showed the greatest cation losses, but this may have been a reflection of past treatments. The smallest losses were reported from the white pine plantation.

A comparison of cation budgets from the undisturbed watersheds at Coweeta and Hubbard Brook revealed slightly greater losses of sodium, potassium, and magnesium at Coweeta but slightly less losses of calcium than from Hubbard Brook (Johnson and Swank, 1973; Johnson, et al., 1969).

Other studies of nutrient losses from undisturbed eastern forests have been reported by Elwood and Henderson (1973) and Best and Monk (1974).

In a study of the effects of clearcutting on aspen in northern Minnesota, Verry (1971) could detect no changes in the concentrations of various nutrients measured at stream gauging sites the first year after cutting. He attributed the lack of measurable increases in nutrients to several possible factors: 1) insufficient time to allow for significant decomposition, 2) vigorous regeneration, 3) high exchange capacity of the soils, 4) low topography, and 5) nutrients might have been adsorbed by organic colloids or sphagnum moss in a nearby bog area.

Studies on nutrient cycling and the effects of clearcutting in coniferous forests have been conducted mostly in the Pacific Northwest. Prominant among these are Gessel and Cole, 1965; Cole, et al., 1967; Grier and Cole, 1972; and Fredriksen, 1970 and 1972.

An early study by Cole, et al. (1961) designed to demonstrate the utility of tension-plate lysimeters revealed total nitrogen losses (mostly as ammonium) of less than 1.0 kg/ha at a depth of 28 inches from a 30-year-old Douglas-fir stand for a January to July period.

Fredriksen (1970) analysed nutrient levels in a stream draining an area that was clearcut and later burned to remove slash. Losses of all nutrients measured increased following cutting. Following slash burning the second year, nutrient loss was again increased. The second year following burning, loss of nutrients measured decreased over the previous year except for nitrate

which increased almost four times over the control value. Ammonia and magnesium concentrations exceeded maximum permissible Federal concentrations in the stream for 12 days following slash burning (Fredriksen, 1970). Concentrations of both these nutrients decreased to almost undetectable levels following the initial increase. Neal, et al.(1965)(in Fredriksen, 1970) also reported increased ammonium concentrations following slash burning of Douglas-fir. Likens, et al. (1969) suggest that nitrification occurs in mature hardwood forests in New Hampshire but the forest is very efficient in utilizing ammonia and/or nitrate. The removal of the forest vegetation results in increased oxidation of ammonia to nitrate and its subsequent loss in drainage water.

Fredriksen (1972) reported on the loss of various nutrients from an undisturbed watershed at the H. J. Andrews Experimental Forest. Losses of cations were higher than any reported elsewhere in the Pacific Northwest. Losses of phosphorus and calcium were an order of magnitude greater than those reported by Cole, et al. (1967). Losses of calcium, magnesium, and sodium were approximately four to five times greater than losses from the Hubbard Brook control watershed (Likens, et al., 1970).

The primary anion lost at the H. J. Andrews site was bicarbonate (Fredriksen, 1970), in contrast to the Hubbard Brook study, but consistent with the finding of McColl and Cole (1968) for a similar vegetation type.

Fredriksen (1970) speculated that even the small additions of nitrogen and phosphorus that resulted following cutting and burning, if fully utilized, could result in a significant increase in primary production in infertile mountain streams.

The study by Stottlemyer (1968) appears to represent the only available literature on nutrient losses from lodgepole pine forests. Four cations, Calcium, magnesium, sodium, and potassium were measured in precipitation and streams at the Fraser Experimental Forest, Colorado. Equal total concentration of cations were recorded for both snow and rain. It was estimated that the annual input of cations through precipitation was about 15 kg/ha while annual losses of cations measured were estimated to be about 26 to 29 kg/ha, or a net loss of about 14 kg/ha. Nitrates were not measured during this study but the author felt that low cation concentrations precluded significant amounts of anions in streams.

Excellent reviews of nutrient effects in natural waters are presented by Keeney (1972), Little (1970), Martin and Goff (no date), and Vollenweider (1967).

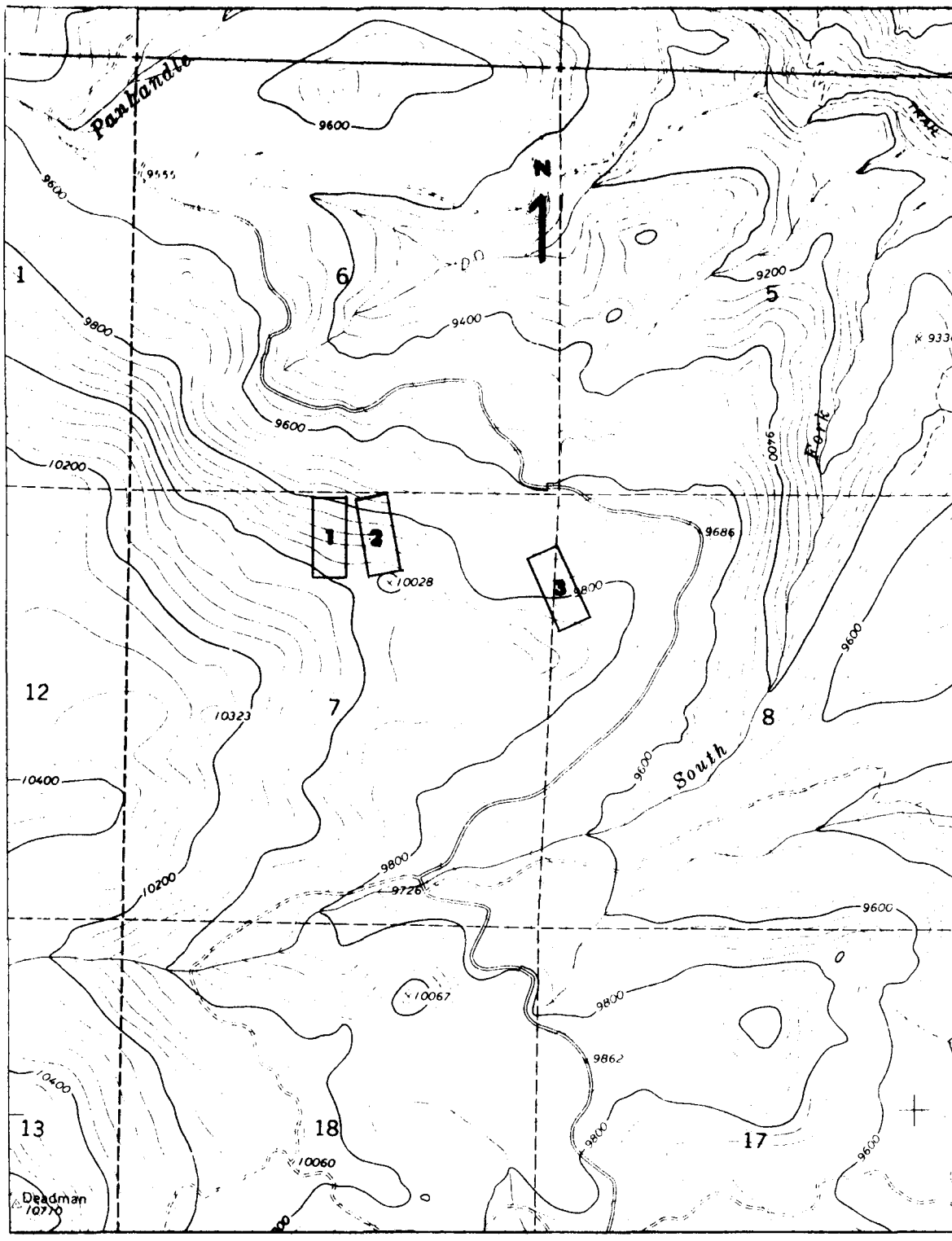
METHODS OF DATA COLLECTION

Site Locations

Study sites were located in the Roosevelt National Forest, approximately 80 km northwest of Fort Collins, Colorado. The area was locally referred to as the Deadman Lookout area, and was located in Sections 7 and 8, T10N, R74W, 6th P.M., in Larimer County. The sites, which ranged in elevation from 2963 to 3048 meters, were at the upper end of the elevational range for lodgepole pine (2134 to 3505 meters) (Moir, 1969). This would be considered to be in the spruce-fir zone (Daubenmire, 1943) in the subalpine forest climax region (Marr, 1961). Soils were sandy loams with a high gravel content originating from decomposed granite, and were alfisols of coarse texture, low fertility, and moderate depth (Soil Survey Staff, 1960, 1965, 1968).

This area was chosen due to its accessibility, a history of past clearcutting operations, and current clearcutting operations. The three selected study sites were located on a north-northwest-facing slope of approximately 10 to 12 percent. Each site was 3.4 hectares (see Figure 1). Site 1 was clearcut in September 1972 following the gathering of baseline data from September 1971 through August 1972. Site 2 was the undisturbed forested "control." Site 3 was clearcut in 1965. Since an attempt was made to locate all three sites similarly with respect to topography, slope angle, and aspect, Sites 1 and 2 were contiguous, while Site 3 was located approximately 560 meters east of Site 2.

Figure 1. Topographic map of study sites, located in Sections 7 and 8, T10N, R74W, 6th P.M., in the Roosevelt National Forest, Larimer County, Colorado.



SCALE 1:24000

1 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

DATUM IS MEAN SEA LEVEL

Soils

Sampling of organic and mineral soil horizons was accomplished during the fall of 1971 and the summers of 1972 and 1973.

Mineral Soils

In September 1971, soil pits were dug to a depth of approximately one meter or until bedrock was encountered, at four locations in each of the three sites. To obtain maximum normal variation within the site, the pits were located equidistantly down the center line of each site, resulting in a stratification into four slope positions. Two mineral soil horizons in the profile were recognized, an A2 horizon (a light colored zone of maximum leaching) and a B2 horizon (an extensive zone of clay accumulation). These horizons were sampled from the south side of each soil pit at depths of seven and 25 centimeters (cm).

During July 1972, a soil auger was used to excavate six soil holes at each of the four slope positions per site, to a depth of about one meter. These holes were oriented horizontally across the slope, with three holes located equidistant (one meter apart) on either side (east and west) of the soil pit (see Figure 2a. Soil samples were collected from these holes from the same horizon depths as in 1971 by use of a hand trowel.

In July 1973, sampling of mineral soil was intensified to more thoroughly characterize each site. Each 3.4 hectare site was gridded into one square meter segments, and sampling coordinates were randomly selected using a table of random numbers. Forty sampling points per

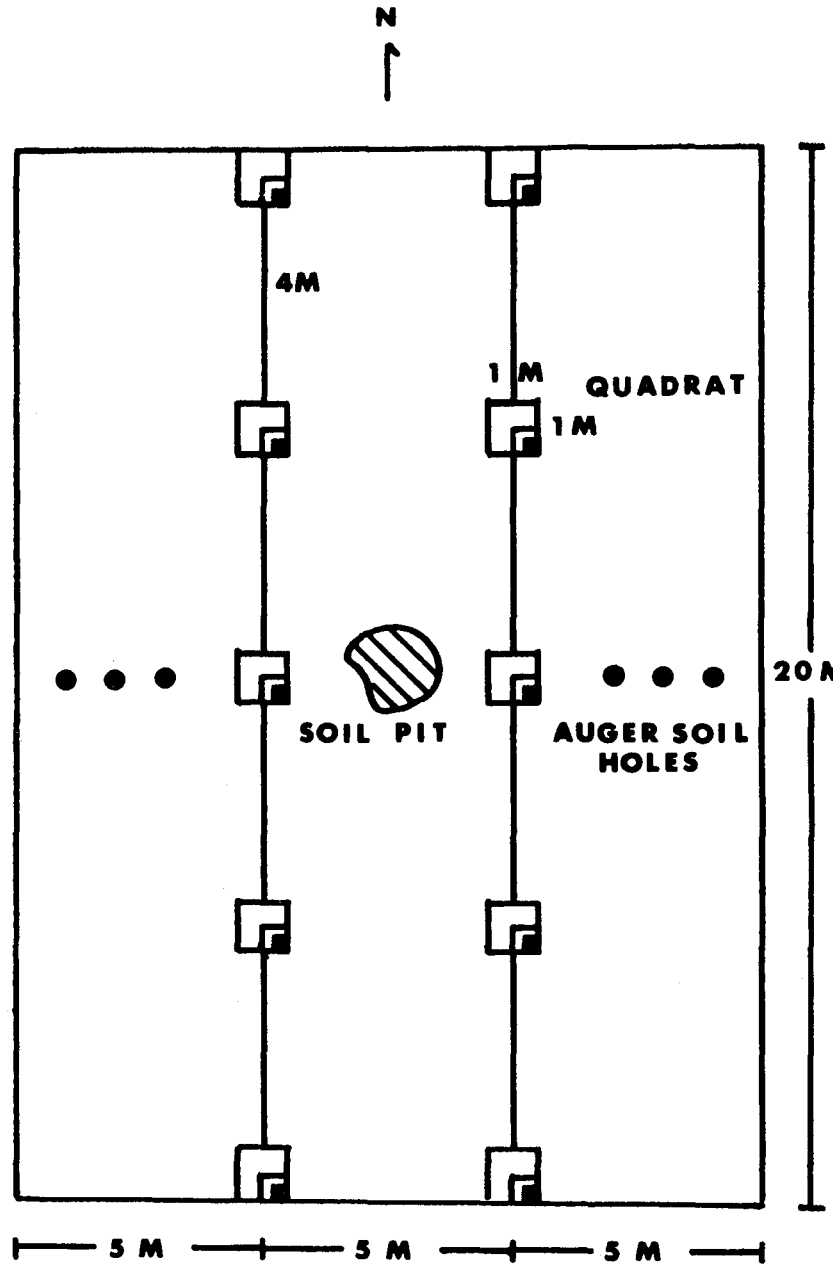


Figure 2a. One of four 15 X 20 meter macroplots used per site for sampling of understory vegetation, forest floor and mineral soils in 1972. For tree reproduction and shrub collections, 1 m^2 quadrats were used, and nested within these were 0.25 m^2 quadrats for collections of herbaceous layer vegetation, and 1/16 m^2 quadrats for forest floor collections.

site were used for collections of mineral soils. Holes were dug by hand using a pick and shovel to a depth of 50 cm, and samples were removed from the same horizon depths as in 1971 and 1972 using a hand trowel.

Descriptions of horizon depth, thickness, boundary characteristics, color (Munsell notation), texture, structure, consistence, presence of roots, and abundance of stones or boulders were made in the field (Soil Survey Staff, 1951, 1960), using the terminology described in the U. S. Forest Service Handbook on Soils (1961). Samples of soils of at least 400 grams were taken from each horizon with sufficient thickness (about five centimeters) to give specimens uncontaminated by material from the upper or lower soil horizon. The samples were placed in plastic-lined soil bags, securely sealed, and brought to the laboratory, prior to drying in an oven at 105° C for 48 hours. Samples for textural analysis were weighed and sieved through a 2 mm mesh screen to fracture the dried clods but not the gravel. The Bouyoucos (1951) hydrometer method as described by Day (1965) was used to determine particle size distribution.

For chemical analysis of mineral soils, ten gram subsamples of the < 2 mm portion were used. Total nitrogen analysis was by the regular macro-Kjeldahl method (Bremner, 1965). Available phosphorus determination followed procedures of Watanabe and Olsen (1965). Exchangeable potassium and calcium were determined using the extraction procedures of Pratt (1965_a). Flame photometry was used to determine potassium and atomic absorption spectrophotometry was used for calcium and magnesium. Cation exchange capacity determinations followed the

sodium saturation procedures of Chapman (1965). Soil pH was measured in a saturation paste using a glass electrode. Nitrate-nitrogen analysis was by the phenoldisulfonic method described in Jackson (1958), and organic matter was determined using the potassium dichromate method of Graham (1959). Duplicate samples were run every five to ten determinations to insure reliability of results.

From the data of chemical analysis of mineral soils in 1971, coefficients of variation were calculated to determine sample sizes required for a 10 percent error, with 90 percent confidence. Based on sample size criteria, it was decided to delete determinations for magnesium and organic matter, due to the large number of samples required to insure reliability of results. Nitrate-nitrogen analysis was discontinued due to undetectable amounts by standard macro-techniques in mineral soils. Determinations for total nitrogen, available phosphorus, exchangeable potassium and calcium, cation exchange capacity, and pH were retained due to a more reasonable sample size requirement, and because of their relative biological importance.

Nutrient quantities in kilograms per hectare (kg/ha) were calculated for the two mineral soil horizons by using corrections for percent gravel and bulk density. Percent gravel was determined during textural analysis. Bulk density measurements were taken by excavating a small hole, collecting the soil in a small metal soil can, and determining the volume of the removed soil by adding a measured amount of millet to the hole from a graduated cylinder. The removed soil was oven-dried for 48 hours at 105° C prior to weighing. Three bulk density measurements per site were made for both mineral soil horizons.

Forest Floor

Organic material was collected from two forest floor horizons for chemical analysis and biomass determinations. The 01 horizon consists of freshly fallen and decomposing needles, twigs, cones, and bark flakes. The 02 horizon is composed of partially decomposing and decomposed organic material, and is not recognizable as to plant origin. In 1971, a 0.25 square meter (m^2) composite sample of each horizon was collected at each pit area (four pits per site). This was done by combining the material collected from four 1/16 m^2 quadrats located one meter (m) in each cardinal direction from the pit excavated for mineral soil sampling. Forest floor material was removed using a sharp knife and cutting along the inside edges of a wooden frame.

In 1972, the 1/16 m^2 quadrats were located differently. Four 15 x 20 m macroplots per site were established equidistant along the centerline of each site, with the soil pit positioned in the center. Within each macroplot, two 20 m transects spaced five m apart were extended parallel to the long dimension of the macroplot (downslope), as shown in Figure 2a. Five 1/16 m^2 quadrats were located at regular intervals along each transect. Four quadrats were randomly selected within each macroplot for forest floor sampling, and organic material was removed as described above. However, the samples were not combined to form composites as in 1971.

In 1973, 40 samples from both organic horizons were collected from each site using the randomly selected coordinates described for mineral soil sampling.

Forest floor samples were placed in plastic-lined soil bags, tightly sealed, and brought to the laboratory. Following drying in an oven at 70° C for 48 hours, the samples were weighed. Preparation for chemical analysis involved grinding, and two different techniques were employed. The 1971 and 1973 samples were ground in a Wiley Mill to pass a 2 mm mesh screen. The 1972 samples were ground with a porcelain mortar-and-pestle type soil grinder, which essentially excludes larger plant materials (e.g., cones, twigs, etc.). Thus, while chemical data for forest floor horizons in 1971 and 1973 represents all litter materials (including the larger woody particles), data for 1972 probably represents a preponderance of needles.

As with mineral soils, nitrogen analysis was by the Kjeldahl method, phosphorus by the sodium bicarbonate extraction method of Watanabe and Olsen (1965), potassium by flame photometry, and calcium by atomic absorption spectrophotometry. Cation exchange capacity and pH were also measured using the procedures described earlier. Magnesium and nitrate-nitrogen were determined in 1971 only.

Vegetation

Trees and understory vegetation were sampled during the summers of 1972 and 1973.

Trees

Four 15 x 20 m macroplots were established equidistant along the centerline of each site, resulting in stratification of the site into four slope positions, as described earlier. These macroplots were used

to determine tree population characteristics. Each tree with a diameter at breast height (d.b.h.) of 2.5 cm or greater within the macroplot was assigned a number, and labelled with a metal tag to assure later identification. The d.b.h. was measured to the nearest 0.25 cm with the aid of a wood caliper. Due to the assymetrical shape of many of the lodgepole pine tree stems, two d.b.h. measurements per tree were made, on the north- and west-facing sides of the tree, and the average value recorded. Tree heights were measured to the nearest 0.3 m by use of a clinometer and employing standard trigonometric principles. The parameters estimated by tree sampling included densities, diameters, and heights, all of which were used for standing crop biomass and nutrient determinations.

Twenty lodgepole pine trees which represented the frequency of occurrence of stems in the major d.b.h. classes were selected for harvest. In 1972, ten of these trees were harvested from Site 1 prior to the beginning of clearcutting operations in September. In 1973, ten additional lodgepole pine trees were cut from along the edge of Site 1 and Site 2.

Each tree was felled on a plastic tarpaulin in order to account for all needles, branches, and cones. Separation criteria were developed to delineate between the various components of the tree. The ground level was used to delineate the trunk from the root system. The largest diameter shoot leading to the top of the crown was treated as the main stem, and the branches were defined as the lateral appendages originating from this stem. All green needles, living branches, and cones were collected in burlap bags and brought to the laboratory.

From each tree 2.5 cm thick discs were removed at one meter intervals along the stem, beginning at ground level. These discs were labelled with the tree number and position along the stem, and placed in plastic bags to prevent loss of bark, prior to returning to the laboratory.

Oven dry weight was obtained for needles, branches and twigs, and cones following drying at 70° C for 48 hours. Subsamples were then ground in a Wiley Mill to pass a 60 mesh screen in preparation for chemical analysis.

Specific gravity was determined in order to calculate aboveground stem biomass on a dry weight basis. The discs were placed in order of their vertical position in the stem and the diameter of each disc was taken with a diameter tape. This value divided by two gave the average radius. Specimens for specific gravity determinations were cut from the sample discs along the average radius in the shape of a wedge. The bark was removed from the wedge and shavings trimmed to give a smooth surface. The wedge samples were then dried at 70° C for 48 hours to determine the oven dry weight. The method of specific gravity determinations is that described by Heinrichs (1954), and is based on the ratio of oven dry weight to the saturated weight. In order to determine the saturated (green) weight, the wedge samples were first put into a large water-filled glass desiccator and subjected to vacuum for several hours. Then, to insure complete saturation, the submerged samples were placed under positive pressure for several hours. A Toledo pan-balance was used to determine saturated weight, and the resultant specific gravity data were used to compute aboveground stem biomass.

For chemical analysis of stem wood and bark, composite samples from each tree were dried, weighed, and ground, as described for preparation of the other tree components. Selection of discs was made from three vertical height positions along the stem: the lowest disc from ground level, the middle disc representing the central tree height position, and the uppermost disc from the top of the stem. Fifty percent of each disc on a weight basis was used for stem wood and bark subsampling to insure that the same proportion of sample from each height position was used for nutrient determinations. The subsamples were combined after grinding to form a composite sample of stem wood or bark for each tree.

Chemical procedures involved digestion of all plant material in a nitric-perchloric acid solution for 12 hours or more. Total nitrogen was determined using the regular macro-Kjeldahl method, total phosphorus by a vanadomolybdate procedure, and total potassium and total calcium by atomic absorption spectrophotometry.

Understory Vegetation

Shrubs, tree reproduction, and herbaceous layer vegetation were sampled in 1972 and 1973 to determine species composition, biomass, and nutrient content. Phytosociological data recorded were species, percent crown cover, and number of individuals by species counted within the plot or subplot. Quantitative characterisitics determined from sampling of understory vegetation were cover, density, frequency, relative values for each, and importance values.

The sampling procedure for tree reproduction and shrubs in 1972 consisted of extending two 20 meter transects parallel to the long

dimension of each 15 x 20 m macroplot and placing five 1 m^2 plots at equally spaced intervals along each transect, as illustrated by Figure 2a. For herbaceous layer vegetation, 0.25 m^2 quadrats were nested within the lower right-hand corner of four randomly selected 1 m^2 plots. Following phytosociological descriptions, the vegetation was removed, bagged, and brought to the laboratory for weighing and chemical analysis.

1973 understory vegetation sampling was intensified to increase sample numbers and more thoroughly represent each site. Sampling points were those used for mineral soils and forest floor collections in 1973. Thus, there were 40, 1 m^2 randomly selected plots per site for tree reproduction and shrub collections, and 40, 1/16 m^2 quadrats nested within the 1 m^2 plots for sampling of herbaceous layer vegetation.

Understory vegetation was oven dried at 70° C for 48 hours prior to weighing for biomass measurements. In preparation for chemical analysis, all vegetation was ground in a Wiley Mill to pass a 60 mesh screen.

There were some differences in how these plant materials were treated between years. In 1972, tree reproduction and shrubs were removed at ground level and combined for biomass and nutrient determinations. In 1973, tree reproduction was kept separate from shrubs, and was removed including the main taproots and divided into the three components of needles, stem and branches, and roots for chemical analysis. Roots were washed free of soil particles prior to analysis. Chemical procedures were those described for tree nutrient determinations.

Logging Residues

Logging residues in Site 3 (the 1965 clearcut site) were sampled in 1972, using the planar intercept technique of Brown (1971). Ten 1/1000 acre circular plots were regularly spaced at 30.2 m intervals along two transects running vertically downslope. Each transect was located 30.2 m from either side of the center line of the site. Four classes of slash were sampled: needles suspended above the forest floor, twigs (< 1 cm diameter), branches (1-10 cm diameter), and stems (> 10 cm diameter). Subsamples were removed from each circular plot and brought to the laboratory for chemical analysis.

Slash in Site 1 (the 1972 clearcut site) was sampled in 1973 using ten 1 m^2 randomly oriented plots. This was done by gridding the site into one square meter segments as described previously, and using random numbers to select sampling points. All logging residues were removed from within the 1 m^2 plots, put into burlap bags, and brought to the laboratory. After separation into needles suspended above the forest floor, twigs, branches, and stems, these materials were dried at 70° C for 48 hours and weighed.

Chemical analysis followed grinding with a Wiley Mill with a 60 mesh screen, and involved the same procedures as those used for trees and understory vegetation.

Statistical Analysis of Soils and Vegetation

For each chemical factor (C.E.C., pH, N, P, K, and Ca for all years, and organic matter, nitrate-N, and Mg in 1971) and each mineral soil and

forest floor horizon (01, 02, A2, and B2), the effect of treatment site (1972 clearcut, forest control, and 1965 clearcut) was tested by analysis of variance. This one-way analysis of variance was also performed on tree reproduction, shrubs, and herbaceous layer vegetation for differences in N, P, K, and Ca content between sites. Analysis of variance was used to test the null hypothesis of no difference between treatment sites. Significant differences at the $\alpha = 0.01$, 0.05, and 0.10 levels were recorded.

Tree stem, living branch, and green needle biomass were estimated through statistical regression techniques. Polynominal regression curves were fitted to the stem, branch, and needle biomass data from the 20 harvested lodgepole pine trees. For example, to fit Y as a function of X_1, the appropriate linear model was $Y = \beta_0 + \beta_1 X_1$, where Y was either stem, branch, or needle biomass in pounds, and X_1 was either D^2H (d.b.h. in inches squared times height in feet) or DH (d.b.h. in inches times height in feet). Similar regression models have been used to derive tree biomass by Ovington et al. (1967), Art and Marks (1971), Johnstone (1971), Landis (1972), and others. The resulting regression equations were used to calculate biomass for each tree measured in the four 15 x 20 m macroplots within either the 1972 clearcut or forest control site. Pound values were converted to kilograms, and tree biomass per unit area (kg/ha) was extrapolated from the sample tree data for each site.

Water Collection and Analysis

Three treatment sites were selected during the fall of 1971. Treatment I was a 3.4 hectare clearcut made in September, 1972, treatment II was a forest control and treatment III was a 1965 clearcut. Within each treatment, four slope positions (plots) were selected on a central transect parallel to the main slope such that the distance between plots and between the upper and lower plots and the edge of the clearcut were equidistant (Figure 2b).

Tension lysimeters capable of collecting soil-water at given depths were employed during the study to monitor solute losses.

Four lysimeters (three tube and one plate) were installed on either side of the central transect at each slope position on a line perpendicular to the central transect which resulted in two "replications" at each plot (Figure 2b).

Plate-tension lysimeters (Cole, 1958) were constructed and installed at eight locations on each treatment site (two replicates at each of four plots). The vacuum reservoir for each plate lysimeter was a one-liter thick-walled glass bottle. The plates were installed by cutting a circular area slightly larger than the plate in the surface soil and then carefully removing this soil core to a depth of 10 cm. The plate lysimeter was then placed in the resulting hole and the soil core replaced on top of the lysimeter and tamped gently into place. After installation there was no visible evidence of the lysimeter. Installation of plate lysimeters at depths deeper than 10 cm was impractical owing to the rocky nature of the soils

To collect soil-water samples at depths greater than 10 cm, tube-tension lysimeters were used. These were constructed after the design developed at Pennsylvania State University (Parizek and Lane, 1970).

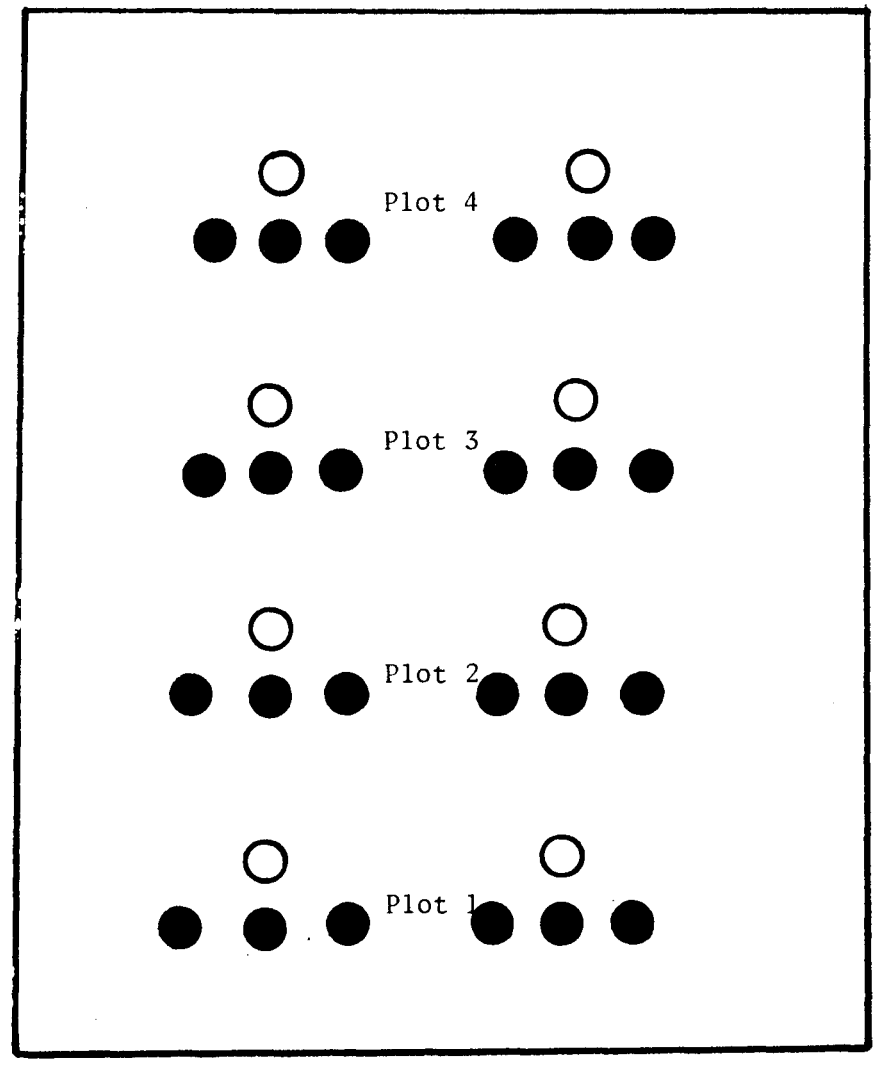


Figure 2b. Schematic representation of lysimeter placements on a treatment. Open circles represent plate-tension lysimeters at a depth of 10 cm. Closed circles represent tube-tension lysimeters at depths of 50, 75, and 100 cm. Top of page is the upslope position.

Tube-tension lysimeters were placed at random along the previously selected transect. Plate lysimeters were installed about two meters upslope from the tube lysimeters. All lysimeters were operational by October, 1973.

A two-way hand pump was used for applying pressure or tension to the lysimeters. A vacuum of approximately 0.3 atm. (160 mm Hg) was applied to each tube lysimeter and approximately 0.6 atm. (300 mm Hg) was applied to the plate lysimeters. The tension of 0.3 atm. was selected because it was assumed that this was in the range of "capillary water" and as such constituted subsurface runoff. The 0.6 atm. tension was selected because water in the upper 10 cm of the soil column was extremely transient and had to be collected as quickly as possible.

Soil-water sampling was conducted from late May, 1973, until mid-October, 1973, and from mid-May, 1974, until the end of July, 1974. During 1973, lysimeters at all depths were sampled and analysed for various solutes. The 1974 sampling, however, did not include the 50 and 10 cm lysimeters from the upper two plots.

Lysimeters were serviced on a weekly basis. Soil-water samples collected were stored in plastic bottles and kept in an ice-filled cooler until they were returned to the laboratory and refrigerated later the same day.

Samples were analysed for nitrate, ammonium, phosphate, and occasionally bicarbonate within two days in the Cooperative Fishery Unit laboratory. Sample pH was determined in the field using a Hellige color comparator. Samples were stored for one week and then combined with the following week's samples to provide sufficient volume for additional analyses. The combined samples were sent to the Soil Testing Laboratory

on the CSU campus where analyses were run for calcium, magnesium, sodium, potassium, sulfate, chloride, bicarbonate, and conductivity. Analysis of sulfate, chloride, phosphate and ammonium were discontinued in 1974 because of time and financial limitations. In addition, several conductivity measurements were made at the Cooperative Fishery Unit laboratory in 1974.

Chemical analyses methods were for the most part taken directly from Standard Methods (A.P.H.A., 1971). The methods used were: Nitrate--phenoldisulfonic acid method using KOH instead of NH_4OH; Ammonium--phenate method; Phosphate--stannous chloride method using a benzene-isobutanol extraction after digestion with H_2SO_4 and HNO_3; Bicarbonate--titrimetric using pH meter; Sulfate-- turbidimetric method using $BaCl_2$ and HCl; Calcium and Magnesium--atomic absorption; Potassium and Sodium--flame photometry; Chloride--silver nitrate-potassium chromate; and Conductance--Beckman model RB3 solu bridge and a Beckman micro-cell with a cell constant of 0.5. A Turner model 350 spectrophotometer was used for colorimetric methods.

An attempt was made to determine precipitation from a series of rain gauges on the three treatment sites. Gauges consisted of a 4 or 8 mill plastic bag which was secured to the bottom of a #10 can (top and bottom removed). The can was then attached by the top rim to a stake and suspended in the vertical position at a height of four feet. Precipitation collected was weighed using a handheld spring balance. Weights were converted to inches of water.

Additional precipitation data were obtained from a storage gauge at Deadman Lookout and from daily records at Red Feather Lakes (U. S. Dept. of Commerce).

Periodic snow surveys were conducted during the winter of 1972-73 and 1973-74, in an attempt to determine maximum snow accumulations on the three treatments. A Mount Rose snow tube was employed for this purpose.

Snow, rain, surface runoff samples, and samples from streams draining cut and uncut areas in the near vicinity of the study site were also collected and subjected to the same chemical analyses as the soil-water samples.

Statistical treatment of the concentration data consisted of an analysis of variance using three treatments, two slope positions (two upper plots combined and two lower plots combined), and two depths (75 and 100 cm) as main sources of variation. Contrasts of grand mean treatment concentrations were made using a modification of Scheffe's S-contrasts (Frayer, 1968). Treatment means and standard errors for 10, 50, and 75 plus 100 cm samples were also calculated without consideration to slope position.

Quantification of nutrient losses from the three treatments was difficult because precipitation measurements were too variable and measurements of evaporation and transpiration were not made. Because of these factors a relative estimate of solute losses was developed. Losses were calculated as the product of mean weekly concentrations

(mg/l) from lysimeters at depths from 75 to 100 cm and mean weekly volumes (liters) at the same depths. Mean weekly volumes were determined by summing water volumes collected from each treatment and dividing by sixteen, the total number of tube lysimeters at these depths on each treatment. This procedure resulted in a lower mean volume because it included several lysimeters on each treatment that did not "produce" any water. Mean concentrations were determined by summing individual concentrations from a given treatment for a given sampling period and dividing by the total number of individual analyses. Although losses calculated in this manner are not quantitative, it was assumed that they do relate to actual losses in some consistent manner and that it is the same for all treatments. These relative losses should then reflect trends of actual losses. Losses were reported as milligrams of a solute collected by an average "deep" lysimeter.

The total weight (milligrams) of each solute collected was calculated during the 1973 period with the exception of phosphate and bicarbonate. During the 1974 period only weights of nitrate collected were determined.

RESULTS AND DISCUSSION

Population Characteristics and Phytosociology

Overstory vegetation in the forest control site and the 1972 clearcut site (prior to clearcutting) was essentially pure, even-aged (ca. 200 years old), closed canopied lodgepole pine *(Pinus contorta* Dougl. var. *latifolia)* in the *Picea engelmanni-Abies lasiocarpa* zone (Daubenmire, 1943). The lodgepole pine stands were homogeneous, one-storied, and trees exhibited nearly uniform stem and crown geometry. The stands appeared to have originated after fire, and most of the trees probably became established within the first decade after the disturbance (Mason, 1915). The stagnation of individual trees was apparent, as increment cores taken from several trees indicated little annual growth over the last 100 years. The inverse relationship between stem density and either diameter or height growth, which has been noted by many foresters (e.g., Smithers, 1956; Alexander, 1965), was also evident. In general, the stand characteristics were similar in respect to elevation and density to Moir and Grier's (1969) LH2 stand in the Roosevelt National Forest in Boulder County, Colorado.

Some population characteristics of lodgepole pine in the 1972 clearcut site (prior to clearcutting) and the forest control site are summarized in Tables 1 and 2, and shown graphically in Figure 3. The stands were dense, with 2417 lodgepole pine stems/ha in the 1972 clearcut and 2142 stems/ha in the forest control site (Table 1). Stem density was

Table 1. Stems per hectare of lodgepole pine and other tree species (d.b.h. $\geq$ 2.5 cm) in the 1972 clearcut and forest control sites.

Site	Macro-plot	Lodgepole Pine	Subalpine Fir	Engelmann Spruce	Total
1972 Clearcut[1]	1	1,400	67	0	1,466
	2	2,900	0	0	2,900
	3	4,800	0	33	4,833
	4	567	833	167	1,567
	Average	2,417	225	50	2,692
Forest Control	1	2,200	0	0	2,200
	2	2,033	967	67	3,067
	3	2,033	433	267	2,733
	4	2,300	100	200	2,600
	Average	2,142	375	133	2,650

[1]Prior to clearcutting.

Table 2. Average d.b.h. and stem density by height classes of lodgepole pine in the 1972 clearcut and forest control sites.

1972 Clearcut[1]			Forest Control		
Height in meters	D.B.H. in cm	No. of stems/ha	Height in Meters	D.B.H. in cm	No. of stems/ha
1.0 - 2.0	2.5	8	1.0 - 2.0	2.5	8
2.1 - 3.0	3.1	133	2.1 - 3.0	4.7	92
3.1 - 4.0	3.8	175	3.1 - 4.0	5.4	158
4.1 - 5.0	6.1	133	4.1 - 5.0	6.8	125
5.1 - 6.0	5.7	150	5.1 - 6.0	8.4	100
6.1 - 7.0	5.8	117	6.1 - 7.0	11.8	75
7.1 - 8.0	8.0	159	7.1 - 8.0	11.1	92
8.1 - 9.0	9.1	150	8.1 - 9.0	13.0	150
9.1 - 10.0	10.6	150	9.1 - 10.0	15.1	342
10.1 - 11.0	14.1	442	10.1 - 11.0	18.3	491
11.1 - 12.0	17.9	292	11.1 - 12.0	20.3	217
12.1 - 13.0	20.1	234	12.1 - 13.0	20.7	150
13.1 - 14.0	20.9	133	13.1 - 14.0	21.8	67
14.1 - 15.0	22.4	108	14.1 - 15.0	21.8	50
15.1 - 16.0	29.6	25	15.1 - 16.0	22.4	25
16.1 - 17.0	18.8	8	16.1 - 17.0	-	0
Mean	Mean	Total	Mean	Mean	Total
9.0	12.4	2,417	8.9	14.0	2,142

[1]Prior to clearcutting.

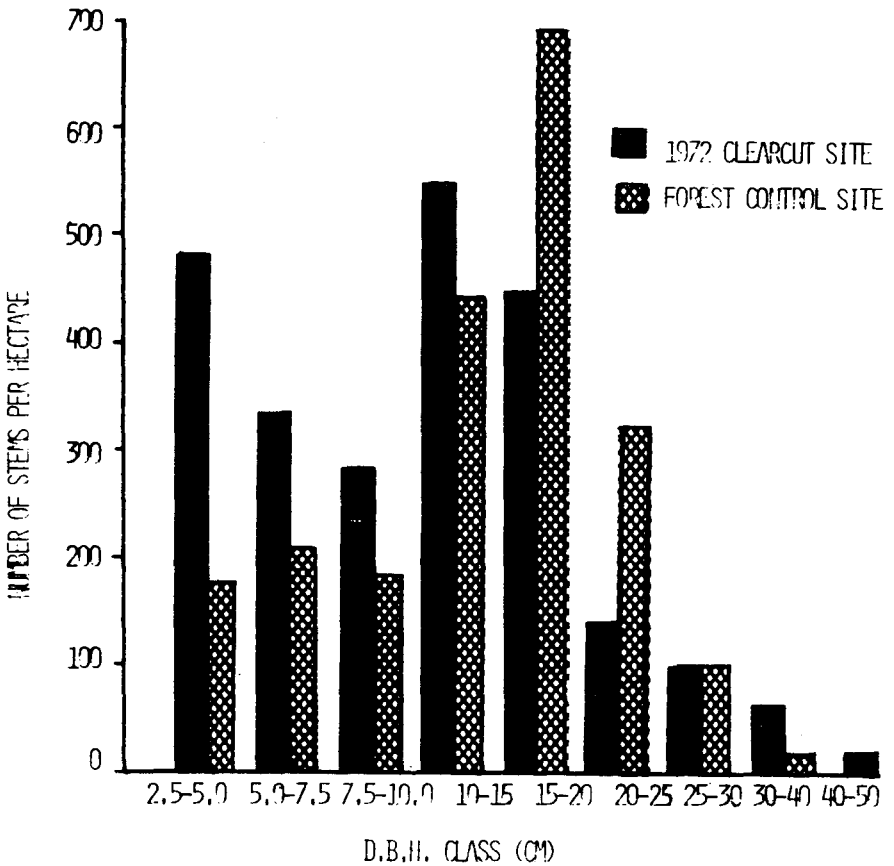


Figure 3. Lodgepole pine stems per hectare by d.b.h. class in two sites.

relatively uniform regardless of slope position in the forest control site, ranging from 2033 to 2300 lodgepole pine stems/ha within the four macroplots (with macroplot 1 representing the uppermost slope position, and macroplot 4 the lowest). In contrast, lodgepole pine stem density in the 1972 clearcut site was much more variable with slope position, ranging from 567 stems/ha in macroplot 4 to 4800 stems/ha in the macroplot directly above (macroplot 3). Subalpine fir and Engelmann spruce were other tree species which occurred in these two sites, accounting for 275 stems/ha in the 1972 clearcut site and 508 stems/ha in the forest control site (Table 1). When all tree species were considered together, total tree stem density was similar in the two sites (2692 stems/ha in the 1972 clearcut and 2650 stems/ha in the forest control site).

Tree heights of lodgepole pine measured in 1972 were similar in the two sites, averaging 9.0 m in the 1972 clearcut and 8.9 m in the forest control site (Table 2). Average d.b.h. was 12.4 cm in the 1972 clearcut and 14.0 cm in the forest control. This larger average d.b.h. of lodgepole pine in the forest control site was reflected in the greater number of stems in the larger d.b.h. classes in this site (Figure 3).

Phytosociological data for understory vegetation are summarized in Table 3 (cover and relative cover), Table 4 (density and relative density), Table 5 (frequency and relative frequency), and Table 6 (importance values). Cover was defined as the percentage of area covered by the crown of the species, density as the average number of individuals per unit of area, and frequency as the percentage of sample

Table 3. Cover and relative cover of understory vegetation in three lodgepole pine sites, based on 40 1.0 m^2 quadrats per site for tree reproduction and shrub species, and 40 0.25 m^2 quadrats per site for herbaceous layer species.

Species	1972 Clearcut[1]		Forest Control		1965 Clearcut	
	Percent Cover	Relative Cover	Percent Cover	Relative Cover	Percent Cover	Relative Cover
			Tree Reproduction			
Abies lasiocarpa	3.6	8.6	9.5	24.8	-	-
Picea engelmanni	2.0	4.7	-	-	-	-
Pinus contorta	1.1	2.6	1.1	2.9	2.1	6.5
			Shrubs			
Juniperus communis	0.5	1.2	1.1	2.9	-	-
Rubus strigosus	-	-	-	-	1.2	3.7
			Herbaceous Layer			
Arnica cordifolia	0.6	0.1	-	-	2.2	6.8
Epilobium angustifolium	-	-	-	-	8.2	25.2
Fragaria ovalis	-	-	-	-	0.1	0.3
Phacelia heterophylla	-	-	-	-	0.8	2.5
Vaccinium scoparium	33.8	82.8	26.6	69.4	6.2	19.1
Grasses and sedges	0.6	0.1	-	-	11.7	35.9

[1]Prior to clearcutting.

Table 4. Density and relative density of understory vegetation in three lodgepole pine sites, based on 40 1.0 m^2 quadrats per site for tree reproduction and shrub species, and 40 0.25 m^2 quadrats per site for herbaceous layer species.

Species	1972 Clearcut[1]		Forest Control		1965 Clearcut	
	Density	Relative Density	Density	Relative Density	Density	Relative Density
			Tree Reproduction			
Abies lasiocarpa	4.0	23.5	18.0	81.8	-	-
Picea engelmanni	2.0	11.7	-	-	-	-
Pinus contorta	2.0	11.7	2.0	9.1	8.0	5.9
			Shrubs			
Juniperus communis	1.0	5.9	2.0	9.1	-	-
Rubus strigosus	-	-	-	-	10.0	7.4
			Herbaceous Layer			
Arnica cordifolia	3.0	17.6	-	-	29.0	21.5
Epilobium angustifolium	-	-	-	-	74.0	54.8
Fragaria ovalis	-	-	-	-	1.0	0.7
Phacelia heterophylla	-	-	-	-	3.0	2.2
Vaccinium scoparium[2]						
Grasses and sedges	5.0	29.6	-	-	11.0	7.5

[1]Prior to clearcutting.

[2]Density of *V. scoparium* not determined due to difficulty of counting individual plants.

Table 5. Frequency and relative frequency of understory vegetation in three lodgepole pine sites, based on 40 1.0 m^2 quadrats per site for tree reproduction and shrub species, and 40 0.25 m^2 quadrats per site for herbaceous layer species.

Species	1972 Clearcut[1]		Forest Control		1965 Clearcut	
	Frequency	Relative Frequency	Frequency	Relative Frequency	Frequency	Relative Frequency
			Tree Reproduction			
Abies lasiocarpa	10.0	7.4	25.0	18.5	-	-
Picea engelmanni	5.0	3.7	-	-	-	-
Pinus contorta	5.0	3.7	5.0	3.7	20.0	10.5
			Shrubs			
Juniperus communis	2.5	1.8	5.0	3.7	-	-
Rubus strigosus	-	-	-	-	10.0	5.3
			Herbaceous Layer			
Arnica cordifolia	7.5	5.6	-	-	12.5	6.6
Epilobium angustifolium	-	-	-	-	47.5	25.0
Fragaria ovalis	-	-	-	-	2.5	1.3
Phacelia heterophylla	-	-	-	-	7.5	4.0
Vaccinium scoparium	97.5	72.2	100.0	74.1	42.5	22.4
Grasses and sedges	7.5	5.6	-	-	47.5	25.0

[1]Prior to clearcutting.

Table 6. Importance values of understory vegetation in three lodgepole pine sites.

Species	1972 Clearcut[1]	Forest Control	1965 Clearcut
		Tree Reproduction	
Abies lasiocarpa	39.5	125.1	-
Picea engelmanni	20.1	-	-
Pinus contorta	18.0	15.7	22.9
		Shrubs	
Juniperus communis	8.9	15.7	-
Rubus strigosus	-	-	16.4
		Herbaceous Layer	
Arnica cordifolia	23.3	-	34.9
Epilobium angustifolium	-	-	105.0
Fragaria ovalis	-	-	2.3
Phacelia heterophylla	-	-	8.7
Vaccinium scoparium	155.5[2]	143.5[2]	41.5[2]
Grasses and sedges	35.3	-	46.0

[1]Prior to clearcutting.

[2]Does not include relative density.

plots in which a species occurred. Relative values were calculated on the basis of the proportion of a species cover, density, or frequency to that for all species in the site. Importance values (I.V.) were computed based on the sum of relative cover, relative density, and relative frequency for each species.

Species numbers were relatively low in the two forested sites in 1972. Other authors who have reported low understory species diversity in lodgepole pine forests include Stahelin (1943), Trappe (1959), Alexander (1966), Moir (1969), Moir and Grier (1969), and Woodmansee (1972). Species diversity increased following clearcutting, which was also the observation of Alexander (1968), Vogl and Ryder (1969), and Basile and Jensen (1971). The greater species diversity in the 1965 clearcut was accounted for by the increase in the number of herbaceous layer species in this site (Tables 3-6). An important herbaceous species in the 1965 clearcut site was *Epilobium angustifolium* L., which constitutes a major part of the successional vegetation which becomes established following disturbances (e.g., fire or cutting) in many of the forests of the western United States (Yerkes, 1960; Dyrness, 1965; Lyon, 1971; Harris, 1972). Other herbaceous species found to occur in the 1965 clearcut site but not in the two forested sites were *Fragaria ovalis* (Lehm.) Rydb. and *Phacelia heterophylla* Pursh. *Arnica cordifolia* Hook. and grasses and sedges occurred in the 1965 clearcut site with higher cover, density, frequency, and importance values than in either of the forested sites. A *Lupinus* sp. was observed to occur exclusively in the 1965 clearcut, but due to low numbers of individuals in this site, it was not sampled.

Vaccinium scoparium occurred in all three sites, but had considerably higher cover, density, frequency, and importance values in the forested sites as compared with the 1965 clearcut (Tables 3-6). Although this species is usually considered a dwarf shrub, it was included in the herbaceous layer due to the similarity of its ecological niche to that of herbaceous vegetation. Evidently *V. scoparium* decreases after clearcutting in these sites; the individuals of this species that were sampled in the 1965 clearcut were usually found in the shelter of slash or residual trees. There was also an apparent decline in numbers and vigor of this species in the 1972 clearcut site. Nine months after clearcutting, it was observed that there were fewer numbers of individual plants remaining, probably as a result of disruption caused by actual harvesting operations. The plants that were remaining, particularly those that were in the open, often appeared chlorotic and had lost their leaves. Trappe (1959) reported that *V. scoparium* almost entirely disappeared from lodgepole pine clearcuts in north-eastern Oregon.

Occurrence of shrub species also differed according to site. *Juniperus communis* L. was sampled only in the two forested sites, while *Rubus strigosus* Michx. occurred exclusively in the 1965 clearcut site. Other shrub species observed to occur only in the 1965 clearcut were *Arctostaphylos uva-ursi* (L.) Spring and a *Rosa* sp.

Subalpine fir and Engelmann spruce tree reproduction (d.b.h. < 2.5 cm) were found to occur only in the two forested sites, while lodgepole pine seedlings were recorded in all three sites. However,

lodgepole pine seedlings were more numerous and had correspondingly higher cover, density, frequency, and importance values in the 1965 clearcut site.

Soils and Forest Floor

Horizon Descriptions and Physical Characteristics

Four soil pits were examined per site and typical soil profiles were described according to the Soil Survey Staff (1960, 1965, and 1968). These soils were classified as alfisols, and detailed horizon descriptions are located in Appendix A.

Johnson and Cline (1965) described the morphology of several typical profiles of montane soils in Colorado, and the soils of my three lodgepole pine sites most closely resembled the well-drained, light-colored, strongly acid soils they describe as podzols. The horizon sequence in my sites, which consists of a surface litter layer 2 to 5 cm thick, a light yellowish brown A2 forming the uppermost mineral horizon, and an extensive lower B2 horizon, is similar to Retzer's (1961) and the Soil Conservation Service's (1967) description of Bobtail gravelly loams occurring on well-drained mountain slopes forested with lodgepole pine in the Fraser Alpine Area in Colorado. This A2-B2 sequence of a bisequel profile was also reported by Moir (1969) to occur in Gray Wooded soils in lodgepole pine forests on the east slope of the Front Range in Colorado.

The O1 and O2 horizons were well differentiated and 2 to 12 cm thick, consisting of undecomposed and partly decomposed pine needles,

twigs, cones, and bark. While the O1 horizons in the forested sites were composed of freshly fallen and partially decomposed organic materials (approximately 90% needles by weight), the O2 horizons were generally unrecognizable as to plant origin due to advanced stages of decomposition. This horizon was held together as a mat by many *V. scoparium* roots. Other studies have cited the distribution of *Vaccinium* spp. rhizomes and roots as mainly in the litter horizons (Flower-Ellis, 1971; Woodmansee, 1972). Moir and Grier (1969) described the forest floors under several lodgepole pine stands in detail, in L, F, and H terminology.

The A2 horizons were continuous, well-expressed, and 6 to 27 cm thick. Dry color was light yellowish brown. The large majority of pine roots occurred in this upper mineral horizon.

The B2 horizon was usually strongly developed, with a clear demarcation between it and the A2 horizon above. Clay films were distinct and complete on peds and in pores. There was little tendency toward structure, and coarse weathered material and stones were abundant.

Rock outcrops were the dominant features causing variations in soil depth and profile expression. Stones and fallen logs were frequently encountered, which also contributed to variability.

Physical factors for the two mineral soil horizons in each of the three sites are summarized in Table 7. These soils were sandy clay loams, or in some cases, clay loams. There was a predominance of large sized soil particles (e.g., gravel and sand). Bulk density values were relatively low, ranging from 0.82 to 0.95, reflecting the high porosity of these soils.

Table 7. Soil textural analysis and physical factors in three lodgepole pine sites.

Site	Horizon	Percent Gravel	Percent Sand	Percent Silt	Percent Clay	Bulk Density
	A2	36	56	22	22	0.84
		26	51	24	25	0.80
1972	Average	31	54	23	24	0.82
Clear-cut[1]	B2	29	55	13	32	0.77
		36	57	15	28	0.86
	Average	32	56	14	30	0.82
	A2	36	51	23	26	1.32
		32	41	27	32	0.80
		38	46	27	27	0.66
Forest	Average	35	46	26	28	0.93
Control	B2	39	53	17	30	0.88
		37	46	23	31	1.06
		26	60	18	22	0.90
	Average	34	53	19	28	0.95
	A2	32	46	29	25	0.78
		50	54	23	23	1.32
		40	58	19	23	0.67
1965	Average	41	53	24	24	0.92
Clear-cut	B2	50	42	23	35	0.87
		49	52	15	33	1.01
		40	50	15	35	0.93
	Average	46	48	18	34	0.94

[1]Subsequent to clearcutting.

Chemical Analysis

Certain chemical properties of the forest floor and mineral soils in each of the three sites were analyzed either in 1971 only, or in 1971, 1972, and 1973, in order to determine clearcutting effects on soil nutrients. Sampling numbers and procedures differed according to year, as described in the Methods of Data Collection. Perhaps less confidence should be given to the 1971 data because of the very small sample size per site (n = 4) as compared with sample numbers in 1972 (n = 24) and 1973 (n = 40). The chemical properties measured all three years included pH, C.E.C., total N, available P, and exchangeable K and Ca, and data are presented graphically in Figures 4-9. Chemical properties measured in 1971 only were percent organic matter, nitrate-N, and exchangeable magnesium (Mg), and results are summarized in Tables 8, 9, and 10. Means, standard deviations, ranges, and F test significance levels between sites for pH, C.E.C., total N, available P, and exchangeable K and Ca for 1971, 1972, and 1973 are tabulated in Appendix B, Tables 1-6. Means, standard deviations, ranges, and F test significance levels between sites for organic matter, nitrate-N, and exchangeable Mg in 1971 are tabulated in text Tables 8, 9, and 10.

Percent organic matter of mineral horizons was relatively low when compared to agricultural soils (Buckman and Brady, 1969). Table 8 indicates values ranged from 1.1 to 1.5 percent in A2 horizons, and from 0.6 to 0.9 percent in B2 horizons, and decreased with depth. These low organic matter percentages might reflect the presence of a well-defined 02 forest floor horizon which does not mix with the mineral material of the A2 horizon below. Percent organic matter in the B2

Table 8. Means, standard deviations, and ranges for percent organic matter in two lodgepole pine soil horizons in 1971.

Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
A2	1.2±0.4 (0.7-1.6)	1.5±0.6 (0.7-1.6)	1.1±0.8 (0.5-2.0)	
B2	0.8±0.4 (0.5-1.2)	0.9±0.1 (0.8-1.0)	0.6±0.3 (0.1-0.7)	**

[1]Prior to clearcutting.

**Significant at $\alpha = 0.01$ level.

horizon of the 1965 clearcut site was significantly lower at the $\alpha = 0.01$ level than in the corresponding mineral soil horizons of the other two forested sites. Lower B2 organic matter percentages might be related to more rapid decomposition rates following the clear-cutting of this site.

Figure 4 depicts the pH of the four soil horizons in the three lodgepole pine sites for three subsequent years. Forest floor and mineral soil horizons were very strongly acid, ranging from 4.2 to 4.8 in O1 and O2 organic horizons, and from 3.7 to 5.3 in A2 and B2 mineral horizons. The values obtained for mineral horizons were from 1.2 pH units lower to 0.4 pH units higher than those reported by Retzer (1962) for the Bobtail gravelly sandy loams in the Frazer Alpine Area. There was a tendency for increase in pH with increasing depth in mineral soils, as Lutz and Chandler (1946) and Ovington (1953) suggested should be expected. Thus, the pH of B2 horizons was usually higher than the pH of the A2 horizons directly above, for all sites and all years. This trend in pH might be related to the increase in exchangeable base content in the B2 horizon as compared with the A2 horizon. Buckman and Brady (1969) in reviewing the effect of Ca on soil pH, stated that generally, hydrogen ion activity decreases when Ca ion activity increases. Exchangeable Ca levels were higher in B2 horizons of all sites for all years compared to A2 horizons (Appendix B, Table 6). Additional evidence for the inverse relationship between Ca ion activity and hydrogen ion activity was provided by data for the pH and exchangeable Ca levels in the 1965 clearcut mineral soils. 1972 and 1973 data indicated significantly higher ($\alpha = 0.01$) pH levels in

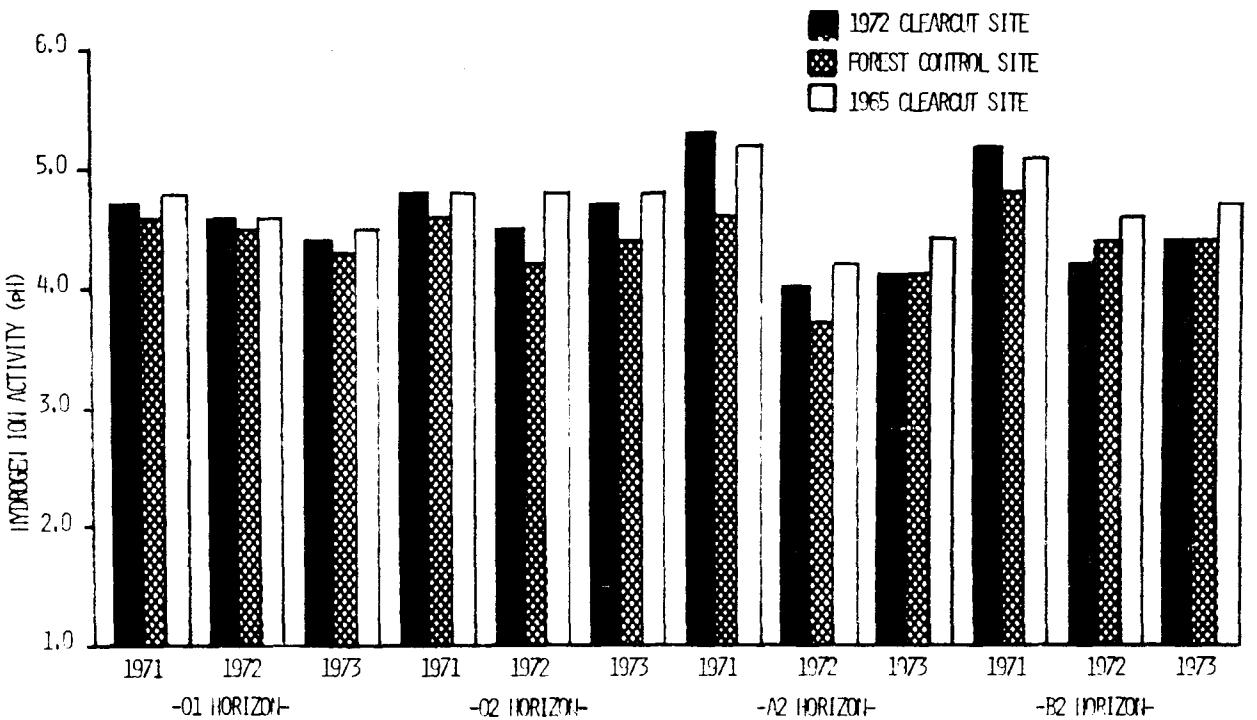


Figure 4. Hydrogen ion activitv (pH) of four soil horizons in three lodgepole pine sites for three subsequent years.

the A2 and B2 horizons of the 1965 clearcut site as compared with corresponding horizons of the other two sites (Appendix B, Table 1). Exchangeable Ca is also significantly higher in these horizons in the 1965 clearcut site than in the other two sites (Appendix B, Table 6).

Cation exchange capacities ranged from 56.3 to 74.0 meq/100 g for forest floor horizons, and from 6.0 to 13.1 meq/100 g in mineral soil horizons (Figure 5). However, due to the pH dependency of C.E.C., these values determined at pH 8.2 were probably higher than if they had been measured at a pH of 4 or 5, which would be closer to the actual pH levels of these soils (Coleman and Thomas, 1967). The C.E.C. values compared favorably with those reported for the Bobtail gravelly sandy loams of the Frazer area (Retzer, 1962; Soil Conservation Service, 1967). The similarities might result from the lack of development of zones of accumulation of clay and humus colloids in the subsurface horizons, which were non-existent in most of the Fraser watershed soils. There were no consistent C.E.C. differences between sites.

Figure 6 depicts the dramatic decrease in percent total N from the forest floor to the mineral soil horizons. Total N ranged from 0.74 to 1.12 percent in organic horizons, and ranged from 0.02 to 0.08 percent in mineral horizons. Since soil N occurs primarily in organic forms, such as amino acids and amino sugars, it would be expected that most soil N would be in the proteinaceous plant materials comprising the O1 and O2 horizons of the forest floor (Black, 1968). The decrease of percent total N with depth in mineral horizons paralleled the decrease of organic matter, as Lutz and Chandler (1946) indicated should be expected. Percent total N in the O1 and O2 horizons of the

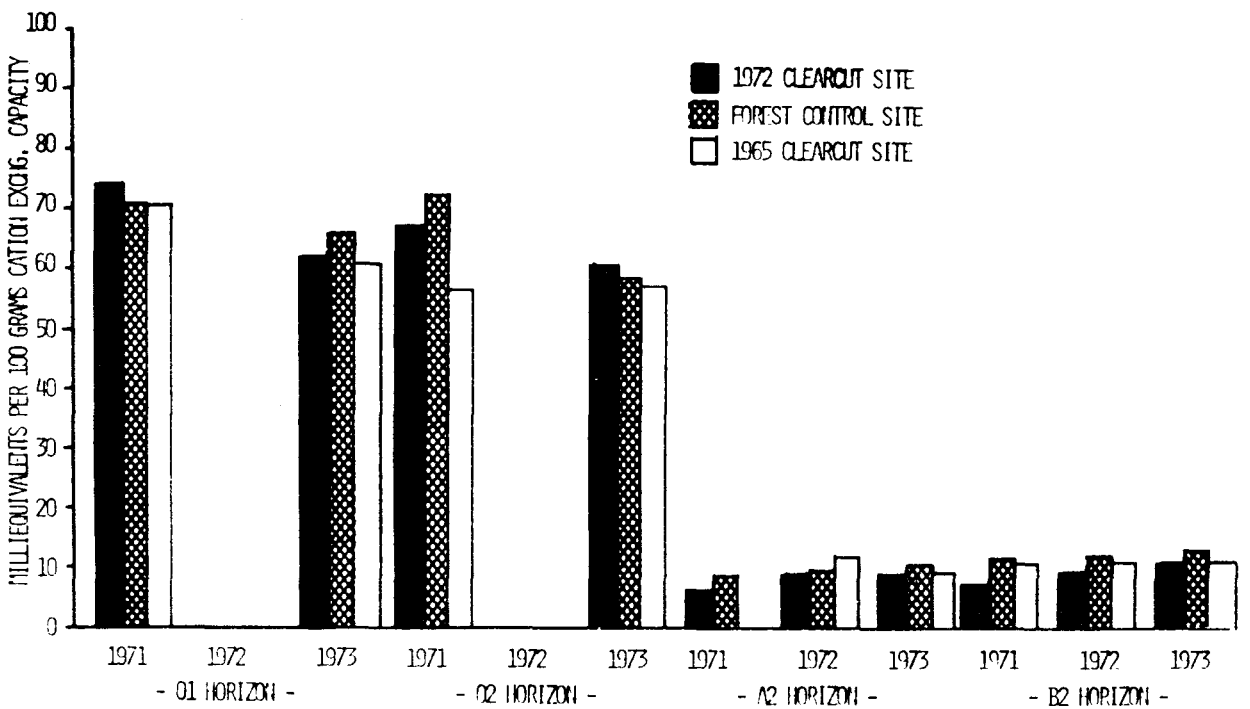


Figure 5. Milliequivalents per 100 grams cation exchange capacity of four soil horizons in three lodgepole pine sites for three subsequent years.

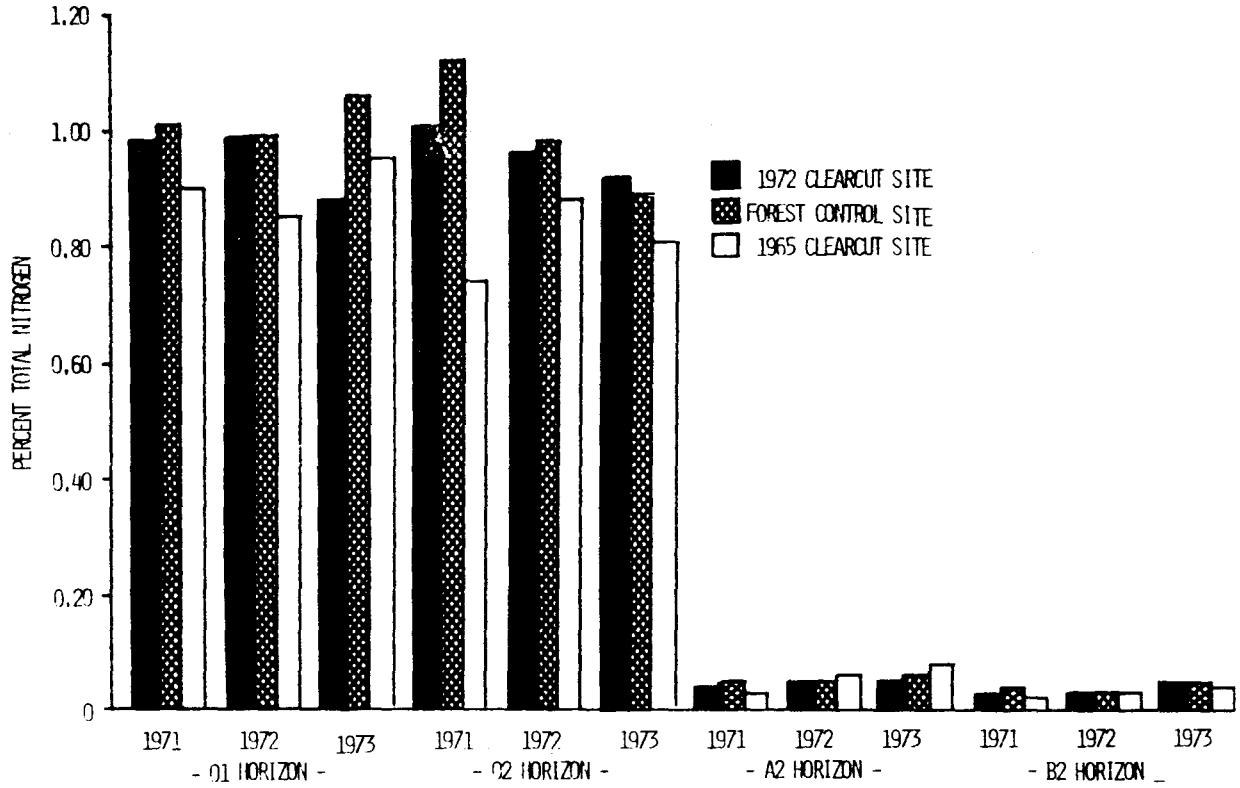


Figure 6. Percent total nitrogen of four soil horizons in three lodgepole pine sites for three subsequent years.

1965 clearcut site was lower than in corresponding horizons in the other two sites, with varying levels of significance (Appendix B, Table 3). The mineral horizons, however, showed no consistent differences between sites. Nitrogen values for the forest floor and mineral horizons were comparable to those reported for other forest ecosystems (Retzer, 1961; Youngberg, 1966; Bollen et al., 1967; Wooldridge, 1968; Metz, Wells, and Kormanik, 1970).

The distribution of nitrate-N in the four soil horizons for the three sites is summarized in Table 9. Amounts of nitrate-N in the forest floor horizons decreased from the 01 to the 02 horizon, to non-detectable levels in the mineral horizons. The indication was that this highly mobile form of N was not being retained or accumulated by the mineral horizons, but instead probably was being rapidly leached through the soil into the groundwater below. Amounts of nitrate-N in the 1965 clearcut forest floor horizons were significantly less than amounts in corresponding horizons in either the forest control or the 1972 clearcut sites, at the $\alpha = 0.01$ level.

Available phosphorus values expressed in parts per million (ppm) for soils from the three sites are depicted in Figure 7. These values can be used here only as relative measures, since the method of determination is reliable only for neutral (pH 7) and slightly basic soils. In addition, mineral soils were oven dried at 105° C, which might tend to give higher P values. However, general trends within horizons and differences between sites can be noted. There was considerable year-to-year variation in the levels of available P in the forest

Table 9. Means, standard deviations, and ranges for ppm nitrate-nitrogen in four lodgepole pine soil horizons in 1971.

Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
01	26.2±8.4 (20.0-38.4)	27.9±1.6 (25.6-29.2)	17.5±1.1 (16.0-18.4)	**
02	15.0±7.2 (10.0-25.6)	18.8±3.1 (15.2-22.0)	10.3±4.0 (7.2-16.0)	**
A2	ND	ND	ND	
B2	ND	ND	ND	

[1]Prior to clearcutting.

**Significant at $\alpha = 0.01$ level.

ND Not detectable

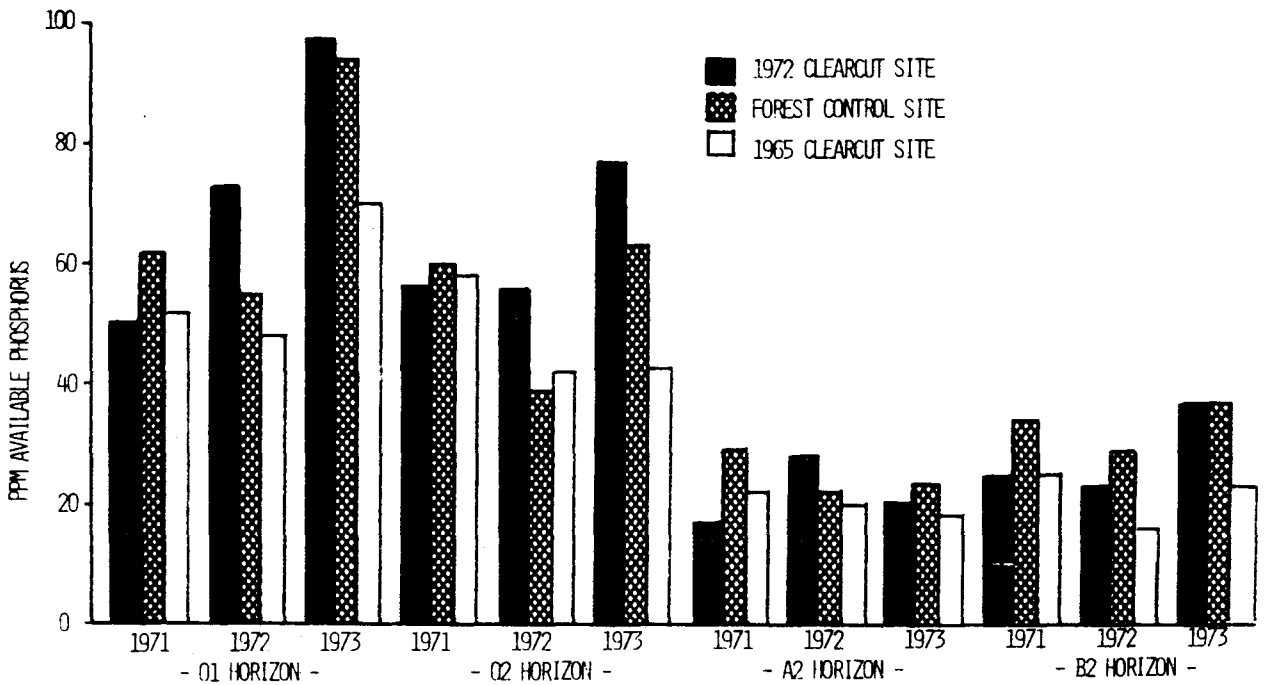


Figure 7. Parts per million available phosphorus of four soil horizons in three lodgepole pine sites for three subsequent years.

floor and mineral soil horizons. This erratic behavior of P was also noted by Woodmansee (1972). Values for the forest floor horizons ranged from 39 to 97 ppm. The 1973 data indicated lower levels of P in the 01 and 02 horizons of the 1965 clearcut site at the $\alpha = 0.05$ and 0.01 levels respectively. Values for the mineral horizons ranged from 16 to 37 ppm, with 1972 and 1973 data indicating that the 1965 clearcut site A2 and B2 horizons had significantly lower P levels at the $\alpha = 0.10$ and 0.01 levels, respectively (Appendix B, Table 4). Available P in forest floor horizons was similar to values reported by Youngberg (1966) and Bollen et al., (1967), but it is difficult to make valid comparisons with other values reported in the literature due to the variety of methods used to extract P.

Exchangeable K ranged from 354 to 808 ppm in organic horizons, and from 68 to 136 ppm in mineral soil horizons (Figure 8). Data for 1971, 1972 and 1973 indicated lower levels of K in the 01 and 02 horizons of the 1965 clearcut site as compared to corresponding horizons in the other sites, at varying levels of significance and non-significance (Appendix B, Table 5). Mineral soil horizons had no clearly discernible trend with depth or difference between sites. Exchangeable K values were uniformly low and comparable to forest soils from other regions of North America (Retzer, 1961, 1962; McFee and Stone, 1965; Ike and Clutter, 1968; Cole and Gessel, 1968; Woodmansee, 1972). Exchangeable K data in the literature is usually expressed in meq/100 g, and therefore must be converted to ppm to be compared with our data.

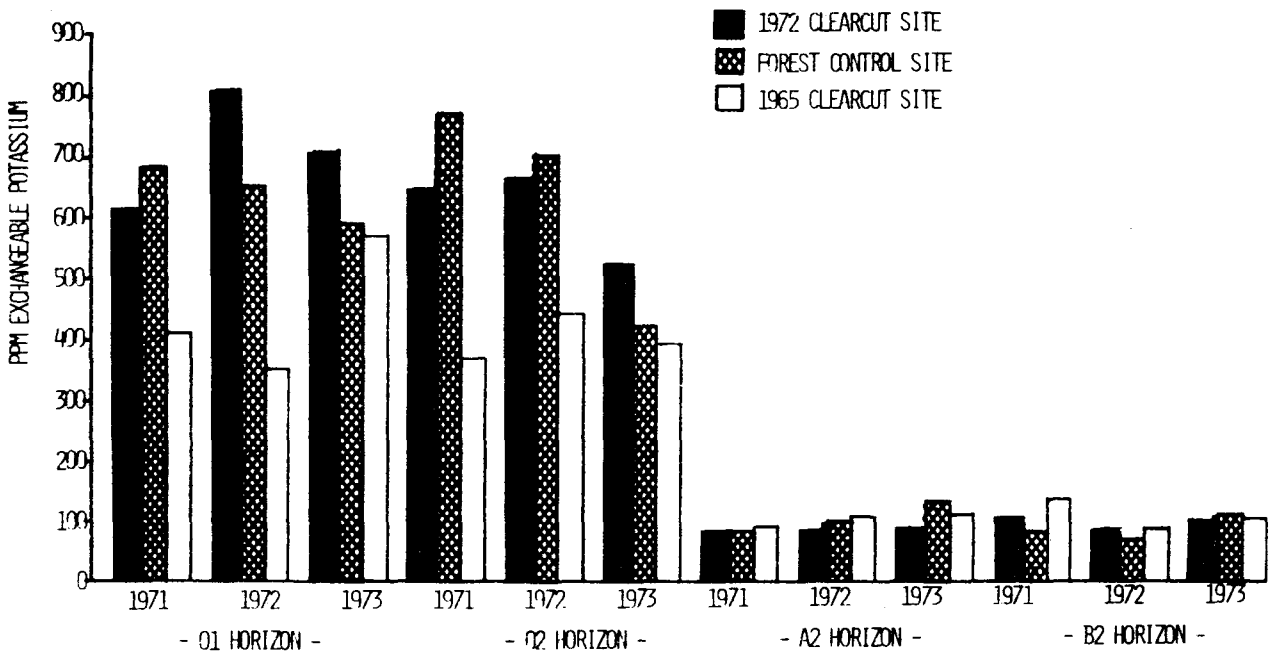


Figure 8. Parts per million exchangeable potassium of four soil horizons in three lodgepole pine sites for three subsequent years.

Exchangeable Ca showed great annual variability in forest floor horizons, ranging from 1637 to 6373 ppm (Figure 9). The amounts found were generally quite similar to those reported by Retzer (1961) for the Fraser area. Exchangeable Ca was found in amounts that were about 2 to 20 times greater than exchangeable K in corresponding 01 and 02 horizons. No consistent significant differences between organic horizons by sites were evident. Mineral horizons ranged from 279 to 603 ppm, and levels in the 1965 clearcut site were significantly higher during most years, corresponding with the higher pH levels in these horizons (Appendix B, Table 6).

Exchangeable Mg was also significantly higher in 1971 in the 1965 clearcut site, in all horizons (Table 10). Levels of Mg decreased with depth from the 01 to the 02 to the A2 horizons, but then showed an increase in the B2 horizon, indicating a deposition at that depth.

If variability in pH, total N, available P, and exchangeable bases in these forest floor and mineral soils was high, it seemed to be the rule rather than the exception. The forest floor, especially the upper 01 horizon, is greatly influenced by the plant material above, while the mineral soil is more influenced by the pedogenic processes occurring below. High variability may reflect the long-term undisturbed condition of the forest, with resultant increased complexity of the forest floor structure. In addition, the young soils of this area might be expected to be more variable, as stated by Harridine (1949).

With such high variability within each site, it was difficult to form generalizations comparing the availability and distribution of nutrients between clearcut and forested sites. Large numbers of samples

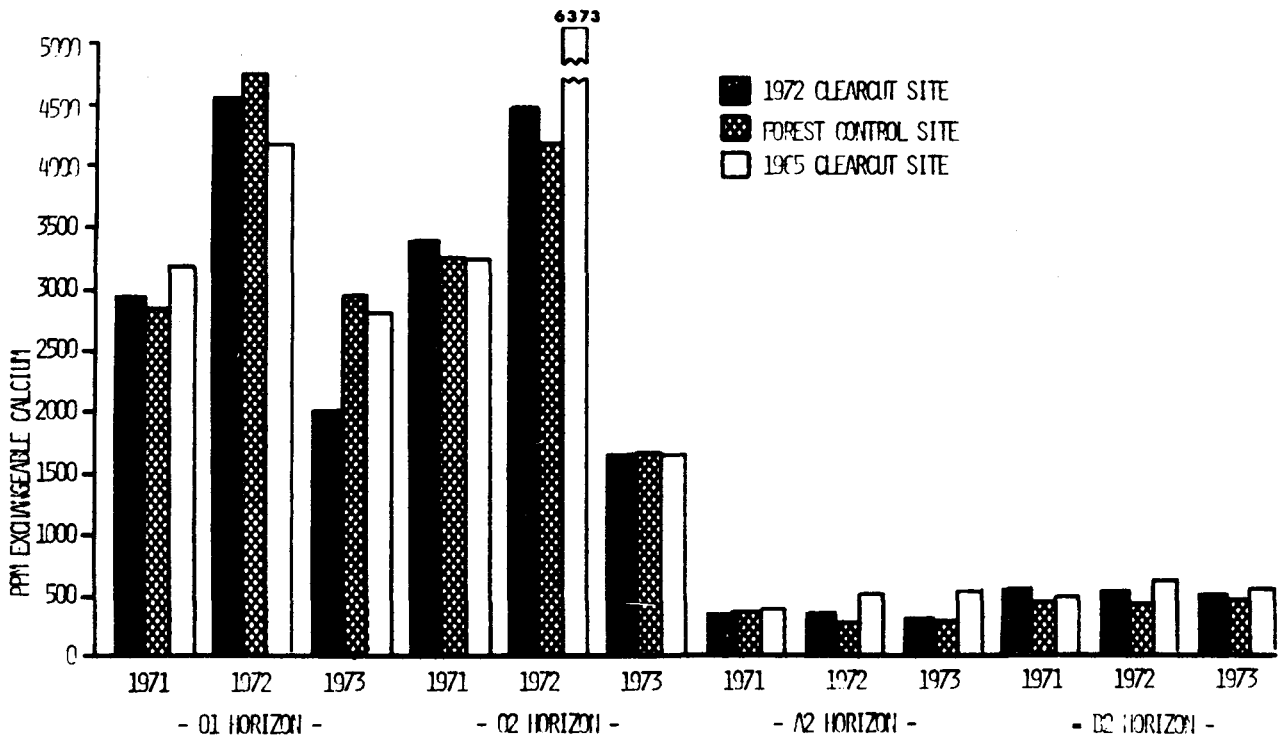


Figure 9. Parts per million exchangeable calcium of four soil horizons in three lodgepole pine sites for three subsequent years.

Table 10. Means, standard deviations, and ranges for ppm exchangeable magnesium in four lodgepole pine soil horizons in 1971.

Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
01	381±45 (332-429)	392±20 (373-412)	425±84 (354-519)	**
02	339±40 (306-391)	342±57 (278-412)	352±145 (207-551)	*
A2	64±12 (47-74)	57±38 (23-109)	79±22 (51-103)	*
B2	113±52 (74-190)	104±31 (60-130)	121±9 (112-132)	**

[1]Prior to clearcutting.

**Significant at $\alpha = 0.01$ level.
*Significant a $\alpha = 0.05$ level.

required analysis before precise estimates of soil parameters could be achieved. Precise sampling required large investments of time and labor because the soils of the area were rocky and sampling involved digging small soil pits rather than taking soil cores. Several studies have indicated that statistically precise sampling is infeasible due to the cost, time, and amount of labor required in collection and analysis of soil samples (Jacob and Klute, 1956; Frankland, Ovington, and MacRae, 1963; Mader, 1963; Metz, Wells, and Swindel, 1966; Ike and Clutter, 1968; Usher, 1970). For example, Anderson and Tiedemann (1970) found on an acid soil (pH 4.8 to 5.3) forested with lodgepole pine, subalpine fir, and Engelmann spruce in Washington, that there was significant periodic seasonal variation in C.E.C., pH, and K contents for seven sampling dates from 1968 to 1969. This could be a factor introducing variability into our results, as the soil sampling in 1971 was conducted during September, while sampling in 1972 and 1973 was in July. Sample preparation techniques are another source of variation. For example, forest floor materials were ground differently in 1972 than they were in 1971 and 1973, which may in part explain the peaks for exchangeable Ca in the O1 and O2 horizons for that year (Figure 9). In addition, sampling size varied according to year, ranging from the largely inadequate number of four soil samples per site in 1971 to 40 samples per site in 1973. Finally, since forest soils are dynamic systems consisting in part of living organisms, variability is to be expected, as in all biological communities.

Despite the high inherent variability and year to year variations in soil chemical properties, there were some important implications of

the effects of clearcutting. The 1972 clearcut site evidentally did not show an immediate detectable response to clearcutting, since soils from that site were sampled nine months subsequent to harvesting operations. In the Hubbard Brook study, the chemical concentration in drainage waters from the cutover watershed did not increase significantly until the second water year after cutting (Likens et al., 1969), and soil responses would be expected to take even longer. The 1965 clearcut however, was significantly different in some soil chemical properties from the other two sites. There were indications of lower percent organic matter in at least one mineral soil horizon, and higher pH levels corresponding to greater amounts of Ca and Mg in the A2 and B2 horizons. Available P levels were lower in mineral horizons for two years. Forest floor horizons in the 1965 clearcut site also showed differences in chemical properties from the other sites. Nitrate -N and exchangeable K were lower in the O1 and O2 horizons of this site for all years of measurement. Available P was at significantly lower levels in 1973.

A possible explanation for these chemical differences might relate to the nature of the forest floor composition of the sites. The organic horizons in the 1965 clearcut site consisted of older materials, deposited from litterfall and clearcutting operations. Examination of the litter comprising the forest floor in this site revealed that the more resistant, woody materials predominated. These are the materials which are typically lower in N, P, and K. Very few needles remained, which are usually quite high in content of these nutrient elements. In contrast, forest floor materials in the other two sites consisted

primarily of needles, and represented a very recent deposition of organic materials from either standing trees (in the case of the forest control site) or from clearcutting (in the 1972 clearcut site). Higher levels of Ca and Mg in mineral soils of the 1965 clearcut resulted from the decomposition of logging residues on the soil surface above.

Biomass Determinations

Nutrients accumulated in the organic horizons of the forest floor, in the mineral soil and in the underlying rocks are the major storage components of the forest ecosystem (Bormann and Likens, 1967; Cole, et al., 1968; Curry, 1971; Grier and Cole, 1972). Estimates of weights (kg/ha) of forest floor and mineral horizons were needed in order to calculate N, P, K, and Ca contents of these ecosystem compartments. Forest floor 01 and 02 horizon weights as determined in 1972 and 1973 are presented in Table 11. Mineral soil weights are indicated in Table 12, and were determined using bulk density (volume weight) as described by Millar, Turk, and Foth (1965) and Buchman and Brady (1969). Nutrient quantities per hectare were then calculated for mineral soils on the basis of bulk density determinations for the whole mineral soil, with corrections for percent gravel. However, corrections were not made for rocks, which were estimated to occupy about 35 percent of the upper 30.5 cm of mineral soil by volume. Nutrient values were calculated for the top one foot (30.5 cm) of mineral soil, which was considered to be the zone of highest root accumulation and available nutrients. Nutrient quantities in the forest floor were based on the oven dry weights of the 01 and 02 horizons.

Table 11 summarizes the effect of clearcutting on forest floor biomass in the 1972 and 1965 clearcut sites. In July 1972, prior to

Table 11. Effect of clearcutting on forest floor biomass in three lodgepole pine sites.

Horizon	Year	1972 Clearcut (kg/ha)	Forest Control (kg/ha)	1965 Clearcut (kg/ha)
01	1972	14,269[1]	14,346	17,009
	1973	24,958[2]	15,625	23,806
02	1972	28,557[1]	30,290	11,046
	1973	27,334[2]	30,476	16,939

[1]Prior to clearcutting.

[2]Subsequent to clearcutting.

clearcutting the 1972 clearcut site in September, biomass estimates of the 01 horizons in the 1972 clearcut and forest control sites were almost identical (14,269 and 14,346 kg/ha respectively). However, sampling in 1973 revealed almost a doubling of the 01 horizon biomass in the 1972 clearcut site (24,958 kg/ha) as compared with the previous year. This increase resulted from the influx of new litter materials as logging residues were deposited on the forest floor during cutting. The 1972 clearcut 01 biomass after clearcutting compared favorably with biomass of the corresponding horizon in the 1965 clearcut in 1973 (23,806 kg/ha).

The 01 biomass estimates in the 1965 clearcut varied between years. Litter materials in this site showed a great deal of spatial variability; wind and rain have been agents that have acted to form patterns of accumulation of litter in some areas as well as persistant bare spots in others. The 1973 data are probably more reliable due to the increase in sampling intensity (16 samples per site were taken in 1972, 40 in 1973).

The length of time following cutting appears to have an effect on the biomass of the 02 horizons as seen in the 1972 and 1965 clearcut sites (Table 11). The 02 horizon biomass of the 1972 clearcut site remained approximately the same between years (28,557 kg/ha in 1972 prior to clearcutting, and 27,334 kg/ha in 1973 subsequent to clearcutting). In addition, values were similar to 02 biomass estimates in the forest control site during both years (30,290 kg/ha in 1972 and 30,476 kg/ha in 1973). However, 02 horizon biomass in the 1965 clearcut appeared to be about half that of either of the other two

sites. This difference in 02 horizon biomass in the 1965 clearcut is probably due to accelerated decomposition during the eight years subsequent to clearcutting. It might be expected that 02 biomass in the 1972 clearcut site would begin to show a corresponding decrease in subsequent years if increased microbiological activity occurs as a result of a more favorable microclimate following clearcutting this site.

Nutrient Quantities

Estimates of the amounts of total N, available P, and exchangeable K and Ca contained in forest floor horizons in 1973 primarily reflected differences in total weight of these organic layers between sites (Table 12). Since 01 horizon biomass in the 1972 and 1965 clearcut sites in 1973 was about double the 01 biomass in the forest control site, amounts of nutrients contained in the 01 horizon of these sites were larger than in the forest control site.

There were 219.6 kg/ha of total N, 2.4 kg/ha of available P, 17.8 kg/ha of exchangeable K, and 57.6 kg/ha of exchangeable Ca in the 01 horizon of the 1972 clearcut site; these values compared relatively well for the 01 of the 1965 clearcut site, which contained 226.2, 1.7, 13.6, and 66.7 kg/ha of N, P. K, and Ca, respectively. However, the forest control site 01 horizon contained lesser amounts of these nutrients, accounting for 165.6, 1.5, 9.2, and 46.1 kg/ha of N, P, K, and Ca, in that order.

The 02 horizon in the 1965 clearcut site had about half the biomass of this horizon in either of the other two sites, and nutrient quantities reflected this difference. There were 137.2 kg/ha of total

Table 12. Forest floor and mineral soil reserves (top 30.5 cm) of nitrogen, phosphorus, potassium, and calcium in 1973.

Site	Horizon	Weight	Total N	Available P	Exchangeable K	Exchangeable Ca
				kg/ha		
1972 Clear-cut[1]	O1	24,958	219.6	2.4	17.8	57.6
	O2	27,334	251.5	2.1	14.2	44.7
	A2	1,249,664	431.1	17.2	77.6	254.4
	B2	1,249,664	424.9	31.4	89.2	397.5
Forest Control	O1	15,625	165.6	1.5	9.2	46.1
	O2	30,476	271.2	1.9	12.8	50.6
	A2	1,417,302	552.8	21.2	117.0	257.0
	B2	1,447,781	477.8	35.4	104.2	416.6
1965 Clear-cut	O1	23,806	226.2	1.7	13.6	66.7
	O2	16,939	137.2	0.7	6.5	27.9
	A2	1,402,061	661.8	14.9	90.2	426.0
	B2	1,432,542	309.4	17.8	78.9	398.4

[1]Subsequent to clearcutting.

N, 0.7 kg/ha of available P, 6.5 kg/ha of exchangeable K, and 27.9 kg/ha of exchangeable Ca in the 1965 clearcut O2 horizon. Nutrient quantities were greater in the 1972 clearcut and forest control O2 horizons, accounting for 251.5, 2.1, 14.2, and 44.7 kg/ha of N, P, K, and Ca, respectively in the 1972 clearcut, and 271.2, 1.9, 12.8, and 50.6 kg/ha in the forest control O2 horizon. Our values for forest floor nutrient quantities were not directly comparable to those of Moir and Grier (1969) or Stottlemyer and Ralston (1970), except for N, since they determined total quantities of these nutrients. Moir and Grier (1969) reported 332 kg/ha of total N in organic horizons in lodgepole pine stands.

Mineral soils had the largest amounts of nutrients because of their relatively large weight (about 3,000,000 kg/ha for the top 30.5 cm). There was a decrease in total N with depth in all three sites, from 431.1 kg/ha (A2 horizon) to 424.9 kg/ha (B2 horizon) in the 1972 clearcut site, from 552.8 to 477.8 kg/ha in the forest control, and from 661.8 to 309.4 kg/ha in the 1965 clearcut site (Table 12). It appeared that the 1965 clearcut site had both a larger N content in its A2 horizon and a smaller N content in its B2 horizon as compared with the other two sites. Amounts of total N in mineral horizons were about twice that found in forest floor horizons.

In contrast to N, available P increased with depth in all three sites, from 17.2 kg/ha (A2 horizon) to 31.4 kg/ha (B2 horizon) in the 1972 clearcut, from 21.2 to 35.4 kg/ha in the forest control, and from 14.9 to 17.8 kg/ha in the 1965 clearcut sites (Table 12). Amounts of available P in mineral soils in the 1965 clearcut site were lower than

in the other two sites. Mineral soil P was 10 to 20 times the amount in organic horizons.

Amounts of exchangeable K ranged from 77.6 to 117.0 kg/ha, and showed no consistent differences between sites or trend with depth (Table 12). Amounts of exchangeable K in mineral horizons were five to 10 times the amount of K contained in the forest floor.

Exchangeable Ca quantities were similar in the 1972 clearcut and forest control mineral soils, and increased with depth. There were 254.4 kg/ha of Ca in the 1972 clearcut A2 horizon, which compared to 257.0 kg/ha in the forest control A2 horizon. There was more exchangeable Ca in the A2 horizon of the 1965 clearcut site (426.0 kg/ha). The B2 horizons in the three sites had similar amounts of Ca, with 397.5 kg/ha in the 1972 clearcut, 416.6 kg/ha in the forest control, and 398.4 kg/ha in the 1965 clearcut sites. Amounts of exchangeable Ca in mineral soils were six to nine times the amounts in forest floor horizons.

Lodgepole Pine Trees

Biomass Determinations

A determination of forest stand biomass was essential to establish nutrient contents of the lodgepole pine trees. By applying percentage nutrient composition to stand dry weight, it was possible to determine the amounts of nutrients removed from the site during clearcutting, as well as quantities of nutrients left on the site as logging residues. Regression equations were calculated from the range of sample trees selected from the stand. Because of the different proportions of

needle, branch, and stem material in trees of different sizes, the 20 sample trees were distributed over the range of tree sizes (ovington and Madgwick, 1959; Rennie, 1966; Attiwell and Ovington, 1968). One tree was omitted from biomass determinations due to a misplaced bag of branches. The entire tree components of green needles and living branches, twigs, and cones were taken into the laboratory to alleviate subsampling problems and minimize error. Thus the quantification of component size for needles and branches, twigs, and cones was made through direct weighing of oven dry material. Stem dry weight was determined through conversion of cubic volume by employing the property of specific gravity. Results for the 19 sample trees are presented in Table 13.

Total biomass increased with tree size (d.b.h.). The largest tree sampled had a biomass of 276.3 kg, but had two main stems and was therefore not used in calculations of regression equations for biomass estimations. The smallest tree sampled had a biomass of 1.0 kg. The variability in stem and crown dimensions of the 19 sample trees was indicated by the variable proportions of individual tree component biomass (stem, branches, twigs, and cones, and needles).

The regression equations shown in Table 14 are the overall equations based on the 18 sample trees. In development of these models, diameter at breast height squared times height (D^2H) were used as the independent variables (Madgwick, 1968; Tadaki, Hatiya, and Tochiaki, 1968; Johnstone, 1971; Landis 1972). In the case of foliage biomass, the best linear model was found

Table 13. Total and component biomass of harvested lodgepole pine trees.

Tree No.	D.B.H. (cm)	Total Tree Biomass (Kg)	Stem Biomass (Kg)	% of Total Tree Biomass	Living Branch Twig and Cone Biomass (Kg)	% of Total Tree Biomass	Green Needle Biomass (Kg)	% of Total Tree Biomass
1[1]	28.7	276.3	199.6	72.2	61.0	22.1	15.7	5.7
2	20.3	75.9	62.3	82.1	10.3	13.6	3.3	4.3
3	20.1	93.8	81.6	87.0	7.1	7.6	5.1	5.4
4	18.3	74.3	61.5	82.8	8.1	10.9	4.7	6.3
5	15.7	43.9	34.9	79.5	5.7	13.0	3.3	7.5
6	15.5	42.4	31.3	73.8	6.6	15.6	4.5	10.6
7	15.0	50.7	41.9	82.6	5.1	10.1	3.7	7.3
8	14.7	41.1	32.3	78.6	6.1	14.8	2.7	6.6
9	14.0	39.6	29.8	75.2	4.9	12.4	4.9	12.4
10	13.5	40.7	29.8	73.2	5.5	13.5	5.4	13.3
11	13.0	32.4	24.0	74.1	4.8	14.8	3.6	11.1
12	11.4	20.6	15.4	74.8	3.3	16.0	1.9	9.2
13	11.2	24.1	21.2	88.0	1.3	5.4	1.6	6.6
14	10.9	28.2	23.1	81.9	2.2	7.8	2.9	10.3
15	10.0	13.0	9.8	75.4	1.0	7.7	2.2	16.9
16	7.6	5.1	3.9	76.5	0.8	15.7	0.4	7.8
17	6.6	7.6	6.9	90.8	0.3	3.9	0.4	5.3
18	4.3	2.2	1.7	77.3	0.3	13.6	0.2	9.1
19	2.5	1.0	0.5	50.0	0.2	20.0	0.3	30.0

[1]Two main stems.

Table 14. Regression equations, correlation coefficients, and standard errors of the estimate, relating D^2H or DH to the biomass of lodgepole pine tree components.

$\hat{Y}$ (stem weight in lbs.) = 0.29 + .0599 D^2H R = 0.971 S.E. = .00367	(diameter at breast height in inches squared times height in feet)
$\hat{Y}$ (branch, twig, and cone weight in lbs.) = 0.80 + .0079 D^2H R = 0.939 S.E. = .00176	(diameter at breast height in inches squared times height in feet)
$\hat{Y}$ (needle weight in lbs.) = 0.43 + .0330 DH R = 0.838 S.E. = .00537	(diameter at breast height in inches times height in feet)

using the independent variable DH. The equations were designed to predict biomass in pounds since calculations for stem dry weight of harvested trees resulted in pounds when cubic volume was converted to stem biomass by employing specific gravity values.

Correlation coefficients (R) were high for each of the three allometric models (Table 14), despite the relative simplicity of the equations. The relationship between D^2H and stem dry weight had a correlation coefficient of 0.971. The regression line for this relationship is depicted in Figure 10. The correlation coefficient for the relationship of D^2H and branch, twig, and cone biomass was 0.939, and the regression line is depicted in Figure 11. The relationship between DH and needle biomass gave a correlation coefficient of 0.838, and the regression line is illustrated in Figure 12.

Once the appropriate linear regressions were established for the sample trees, the total stem, branch, cone, and twig, and needle biomass of lodgepole pine trees in the 1972 clearcut and forest control could be estimated (Table 15). Tree component biomass per hectare was calculated by extrapolation from the macroplots that were used to sample the stand parameters. Results indicated that stem, branch, twig, and cone, and needle biomass was somewhat greater in the 1972 clearcut site (104,322.1 kg/ha) than in the forest control site (100,942.5 kg/ha). This would be expected due to the greater lodgepole

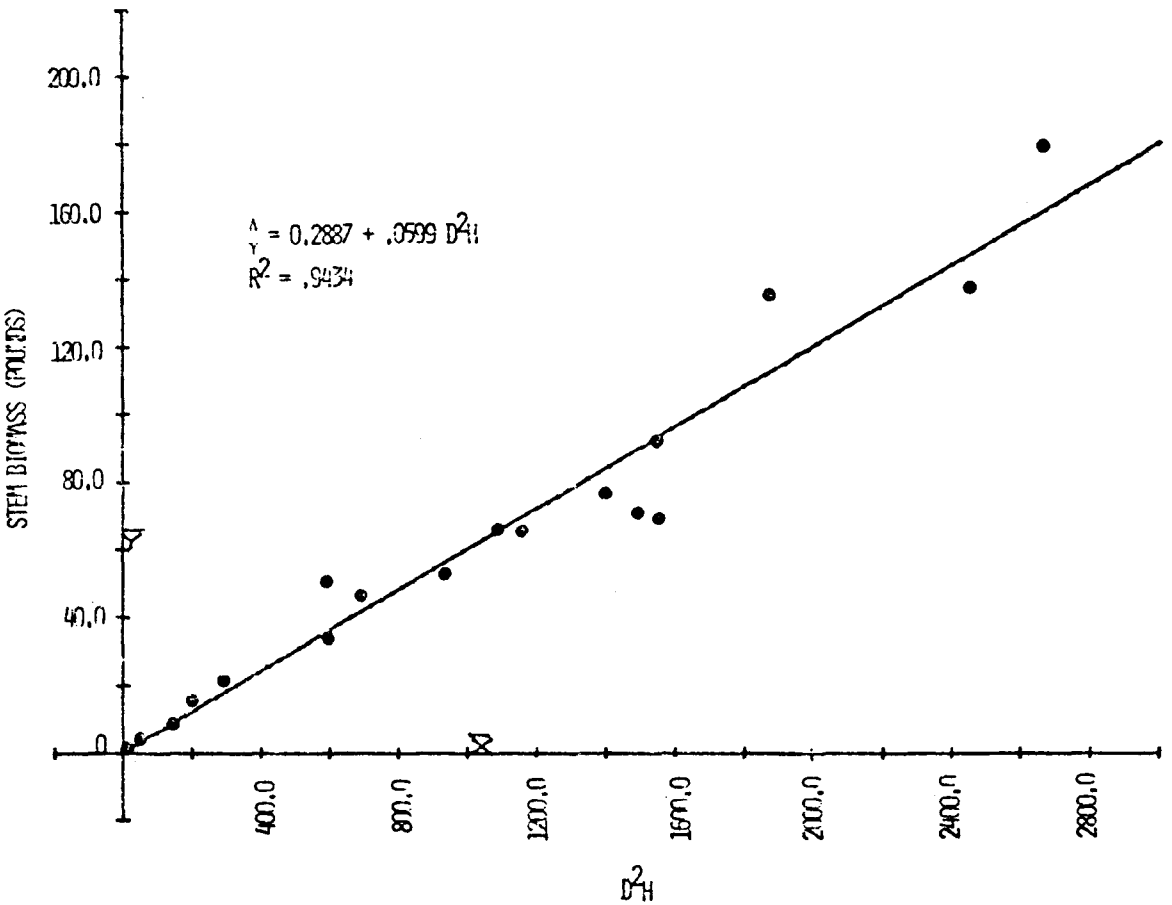


Figure 10. Regression line for the relationship of stem biomass with D^2H.

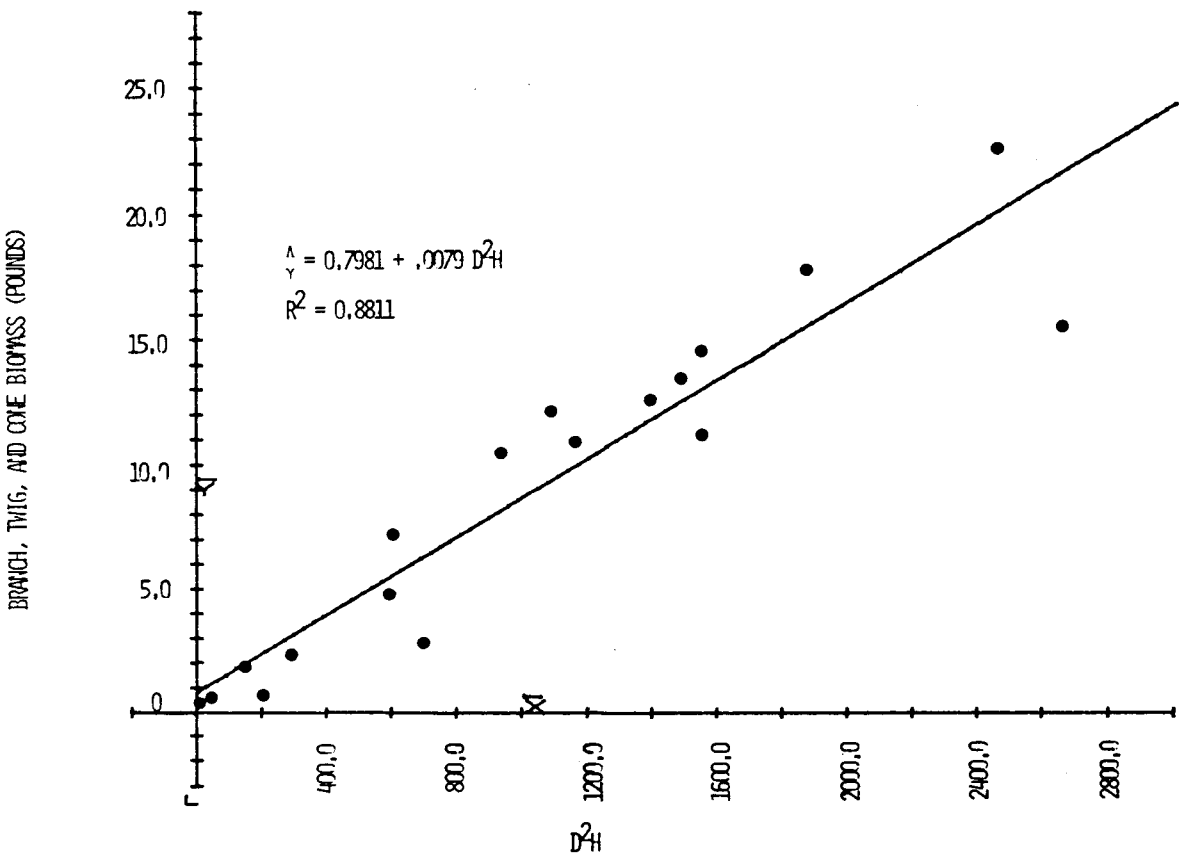


Figure 11. Regression line for the relationship of branch, twig, and cone biomass with D^2H.

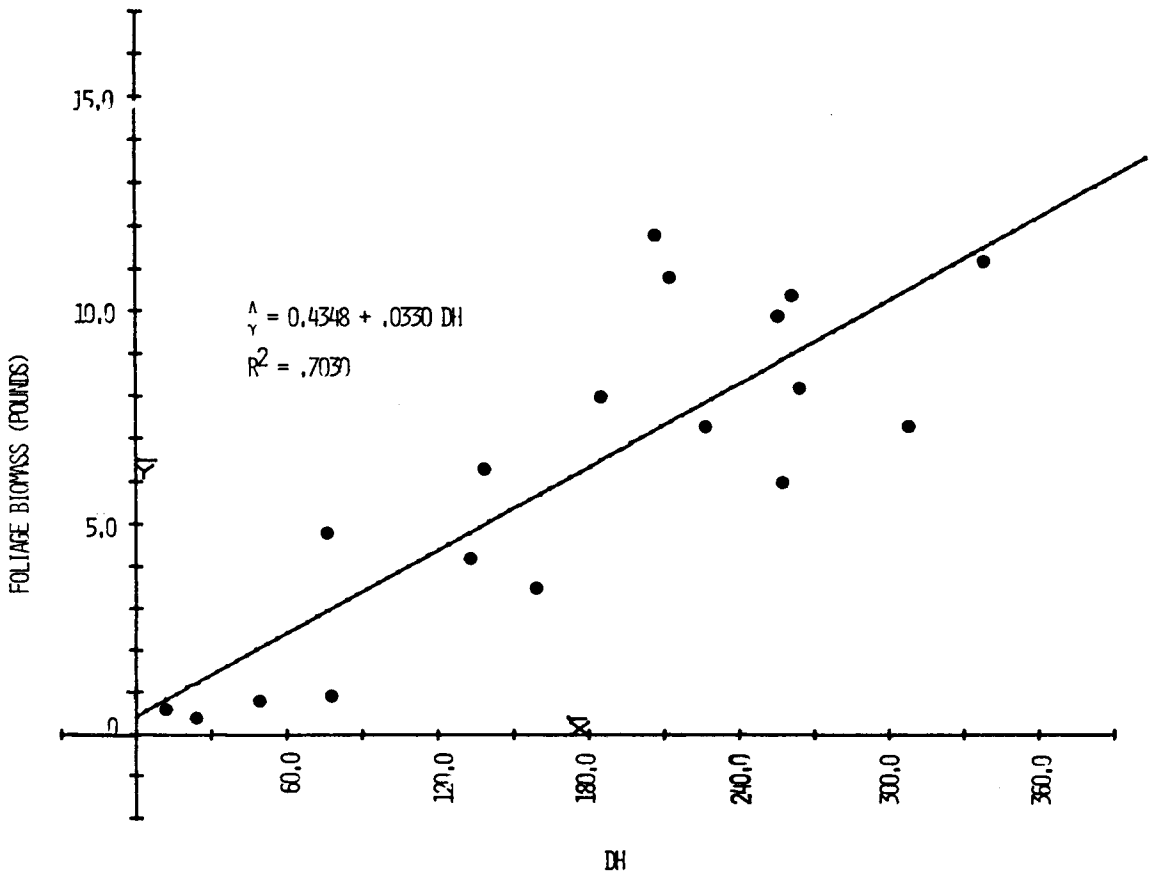


Figure 12. Regression line for the relationship of foliage biomass with DH.

Table 15. Stem density and lodgepole pine stand biomass relationships in the 1972 clearcut and forest control sites.

Site	Macroplot	Density (Stems/ha)	Biomass (kg/ha)			
			Stems	Branches, Twigs and Cones	Green Needles	Total
1972 Clear-cut[1]	1	1,400	95,842.4	12,651.7	5,687.2	114,181.3
	2	2,900	96,942.5	12,796.8	7,444.0	117,183.3
	3	4,800	100,770.8	13,301.7	9,452.1	123,524.6
	4	567	52,510.2	6,924.8	2,964.0	62,399.0
	Average	2,417	86,516.5	11,418.8	6,386.8	104,322.1
Forest Control	1	2,200	90,191.4	11,906.6	6,442.4	108,540.4
	2	2,033	75,697.4	9,995.0	5,718.0	91,410.4
	3	2,033	92,616.8	12,226.4	6,815.9	111,659.1
	4	2,300	75,921.6	10,024.4	6,210.2	92,156.2
	Average	2,142	83,607.6	11,038.2	6,296.7	100,942.5

[1]Prior to clearcutting.

pine stem density in the 1972 clearcut (2417 stems/ha) than in the forest control site (2142 stems/ha). However, while there was an 11.4 percent difference between sites in stem density, there was only a 3.4 percent difference in stem biomass, a 3.3 percent difference in branch, twig, and cone biomass, and a 1.4 percent difference in needle biomass. The lesser number of stems in the larger d.b.h. classes (Figure 3) probably compensated in biomass for the greater number of total stems in the 1972 clearcut, thereby resulting in little difference in comparison to the forest control site.

Nutrient Analysis

Concentrations of total N, P, K, and Ca in lodgepole pine tree components on an oven dry weight basis were determined for the 20 harvested sample trees, and results are presented graphically in Figures 13 through 16 and in tabular form in Appendix C, Table 1. Nutrient contents were determined for the tree components of (1) needles, (2) branches, twigs, and cones (3) branches and twigs, (4) cones, (5) stem bark, (6) stem wood, and (7) stems.

Figure 13 illustrates the distribution of N in these components of lodgepole pine trees. The highest levels were in the needles (0.85 percent), with intermediate levels in branches, twigs, and cones (0.29 to 0.34 percent). Stem wood had the lowest levels of N (0.07) while stem bark was intermediate (0.25 percent). Concentration of N in the total stem (bark and wood included) was at a level between that of stem wood and stem bark (0.11 percent).

Needles also had the highest concentration of P in relation to levels in other tree components, averaging 778 ppm (Figure 14).

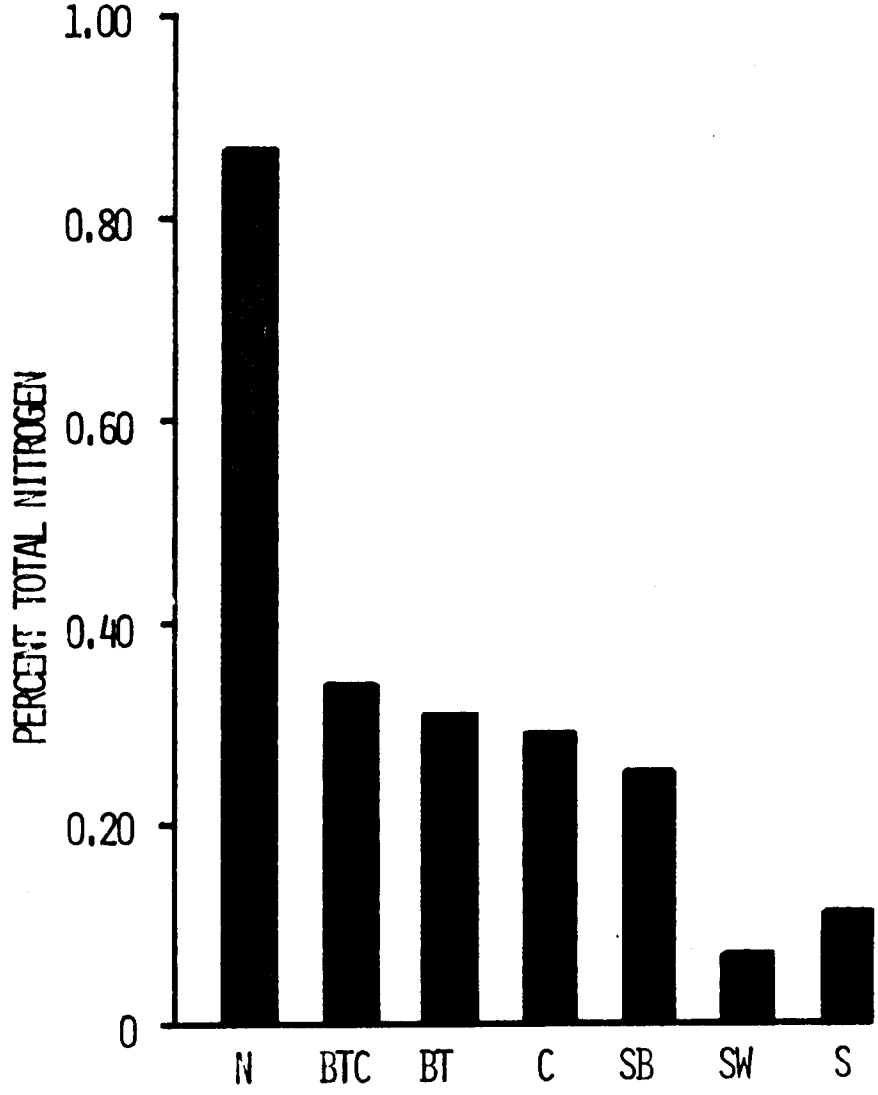


Figure 13. Percent total nitrogen of lodgepole pine tree components. N = needles; BTC = branches, twigs, and cones; BT = branches and twigs; C = cones; SB = stem bark; SW = stem wood; S = stems.

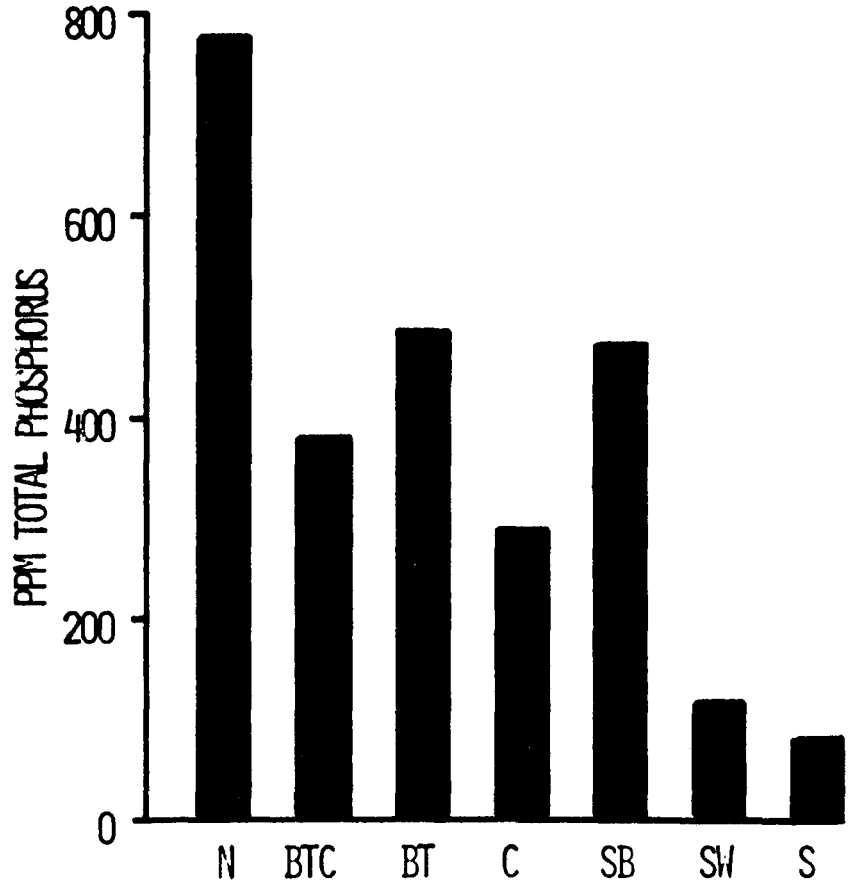


Figure 14. Parts per million total phosphorus of lodgepole pine tree components. N = needles; BTC = branches, twigs, and cones; BT = branches and twigs; C = cones; SB = stem bark; SW = stem wood; S = stems.

Intermediate levels were found in branches and twigs (490 ppm) and stem bark (474 ppm), with lowest levels in stems (78 ppm).

The distributional pattern of K in lodgepole pine tree components was almost identical to that of P (Figure 15). Relatively high levels occurred in needles (2802 ppm), with intermediate concentrations in branches and twigs (1418 ppm) and stem bark (1583 ppm). Lowest levels were found in stem wood (320 ppm) and the total stem (415 ppm).

Calcium tended to accumulate in the bark at high levels (6392 ppm), as indicated in Figure 16. Intermediate levels of Ca occurred in branches, twigs, and cones (3278 ppm) and needles (2889 ppm), with lowest levels in the cones (256 ppm) and stem wood (804 ppm).

Concentrations of these nutrients in lodgepole pine appeared to be in the order of N > Ca = K >> P. This relative ranking of nutrient accumulation is the same as reported for other tree species, including loblolly pine (Nelson, Switzer, and Smith, 1968), black walnut *(Juglans nigra* L.) (Schneider, 1969), white oak *(Quercus alba* L.) (Ralston and Prince, 1965), Virginia pine *(Pinus virginiana* Mill.) (Madgwick, 1968b), red spruce *(Picea rubens* Sarg.), balsam fir *(Abies* spp.), hemlock *(Tsuga* spp.), and northern white cedar *(Thuja occidentalis* L.) (Young and Carpenter, 1967).

The highest concentrations of N, P, K, and Ca were found in the needles and branches and twigs. Bark also had relatively high concentrations, particularly for Ca (Figure 16). In contrast, the woody tissues (e.g., stem wood and cones) had low concentrations of nutrient elements. Since branch and twig samples consisted of wood and bark and the chemical content of bark was much

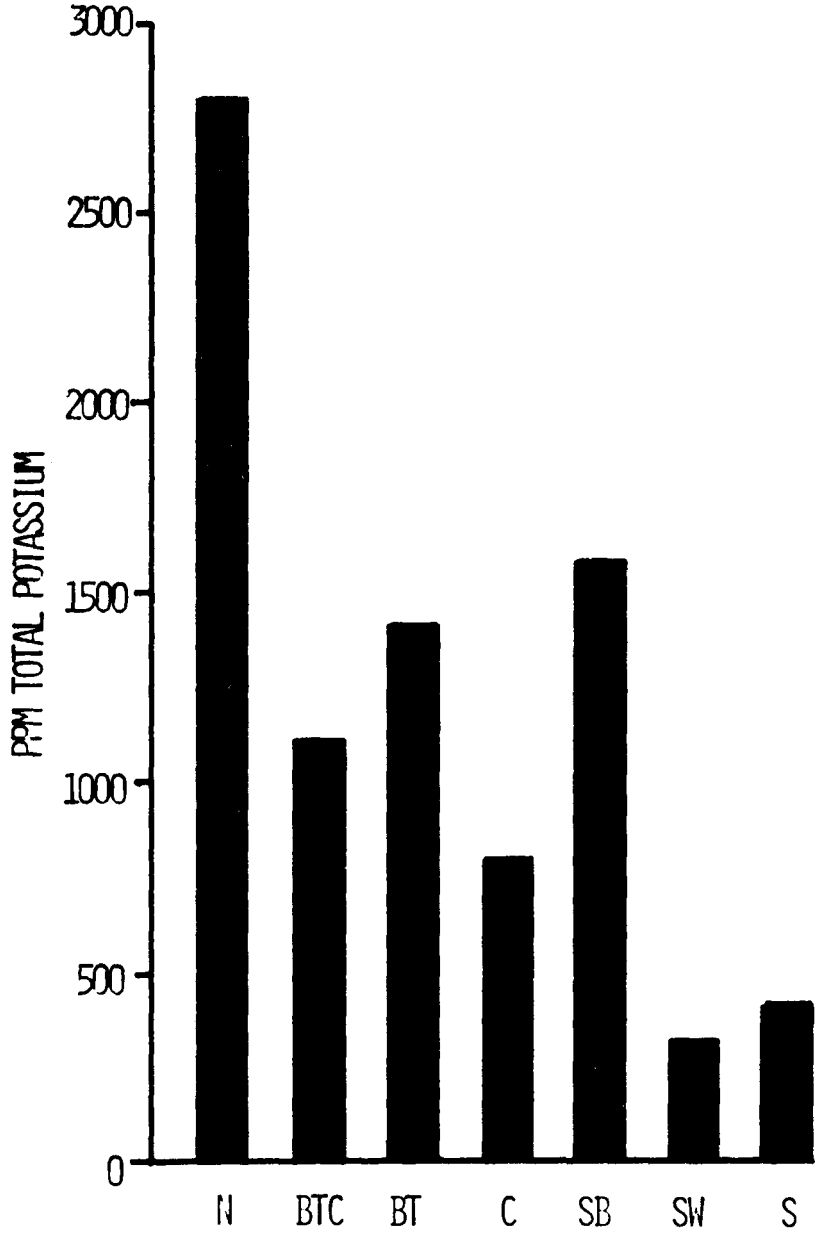


Figure 15. Parts per million total potassium of lodgepole pine tree components. N = needles; BTC = branches, twigs, and cones; BT = branches and twigs; C = cones; SB = stem bark; SW = stem wood; S = stems.

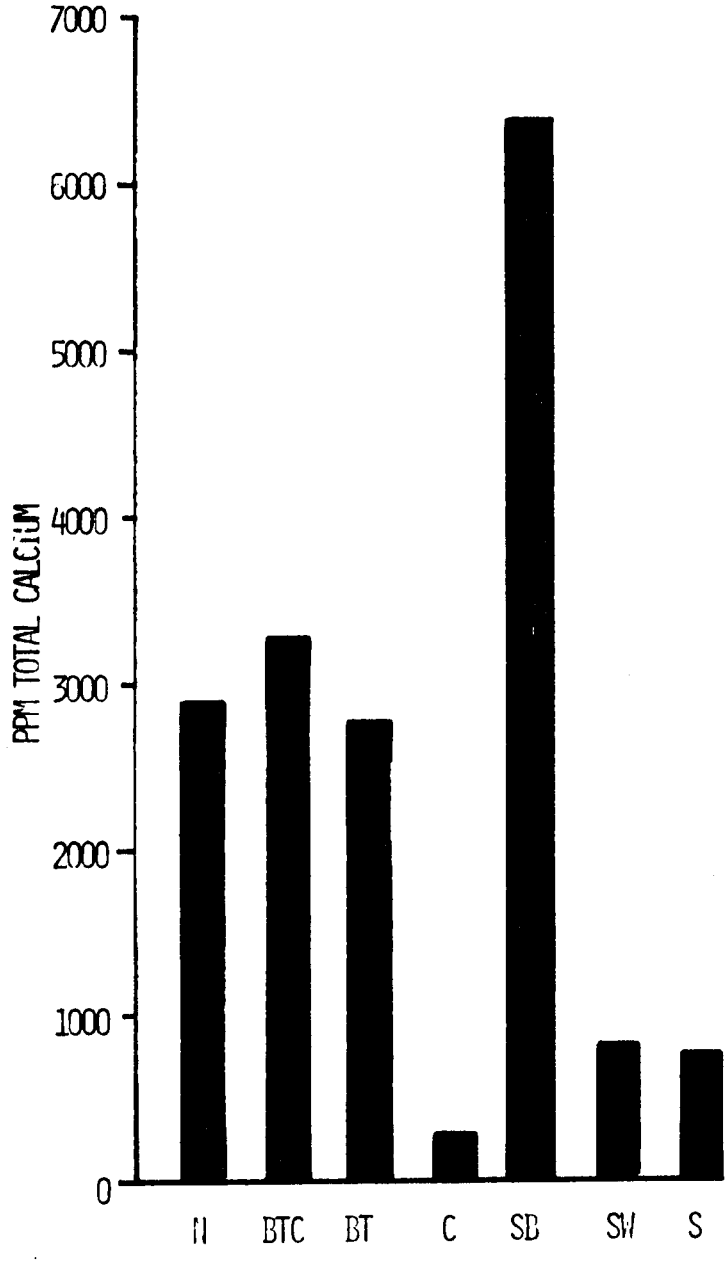


Figure 16. Parts per million total calcium of lodgepole pine tree components. N = needles; BTC = branches, twigs, and cones; BT = branches and twigs; C = cones; SB = stem bark; SW = stem wood; S = stems.

higher than wood, the branch sample concentration probably was "diluted" by a relatively greater percentage of wood in the sample. Branches and twigs had greater nutrient content than stems because phloem and active xylem tissues constituted a larger proportion of the biomass of these components (Ralston and Prince, 1965).

Nutrient content of lodgepole pine tree components appeared to decrease in the order: needles > stem bark > branches, twigs, and cones > stem wood. This sequence would be expected if the distribution and proportions of living tissues and bark in different tree parts is considered (Ralston and Prince, 1965). Curlin (1970) reported that this is also the inverse of the tree biomass distribution sequence, which is further supported by the data in Table 15. This distribution of nutrients within the tree has particular importance in relation to clearcutting, since only stems are usually removed in standard clearcutting procedures and branches, twigs, cones, and needles are left on the site as logging residues, to ultimately return their nutrients to the forest floor and soil horizons below.

Nutrient Removals by Clearcutting

In order to determine the amounts of N, P, K, and Ca exported in tree boles during clearcutting, it was necessary to calculate amounts of these nutrients contained in the forest stands by applying percentage composition values to stand dry weight values derived from the regression models. Table 16 summarizes the distribution of N, P, K, and Ca between the major components of lodgepole pine trees in the 1972 clearcut (prior to clearcutting) and the forest control sites.

Table 16. Distribution of nitrogen, phosphorus, potassium, and calcium between the major components of lodgepole pine trees in the 1972 clearcut and forest control sites.

Site	Tree Component	N		P		K		Ca	
		Kg/ha	% of total	Kg/ha	% of total	Kg/ha	% of total	Kg/ha	% of total
1972 Clear-cut[1]	Stems	95.2	50.6	6.7	41.6	35.9	54.0	64.9	53.8
	Branches, twigs and cones	38.8	20.6	4.4	27.3	12.7	19.1	37.4	31.0
	Needles	54.3	28.8	5.0	31.1	17.9	26.9	18.4	15.2
	Total	188.3	100.0	16.1	100.0	66.5	100.0	120.7	100.0
Forest Control	Stems	92.0	50.3	6.5	41.7	34.7	53.7	62.7	53.5
	Branches, twigs and cones	37.5	20.5	4.2	26.9	12.3	19.1	36.2	30.9
	Needles	53.5	29.2	4.9	31.4	17.6	27.2	18.2	15.6
	Total	183.0	100.0	15.6	100.0	64.6	100.0	117.1	100.0

[1]Prior to clearcutting.

Total nutrient accumulation by lodgepole pine trees was similar in the two sites (391.6 kg/ha in the 1972 clearcut and 383.3 kg/ha in the forest control site). Nutrient accumulation was highest in the stem components of the trees, accounting for 202.7 kg/ha in the 1972 clearcut and 195.9 kg/ha in the forest control (52 percent of the total tree nutrient content). This is not surprising since stems constituted about 83 percent of the total above-ground tree biomass (Table 15). Stems accounted for 50 percent of the total N accumulated in trees, 42 percent of the total P, and 54 percent of the total K and Ca. Nutrient accumulation in needles (95.6 kg/ha in the 1972 clearcut and 94.2 kg/ha in the forest control) was similar to that in branches, twigs, and cones (93.3 and 90.2 kg/ha). Needles comprised only six percent of the total tree above-ground biomass, but accumulated 29 percent of the total N, 31 percent of the total P, 27 percent of the total K, and 15 percent of the total Ca. Branches accounted for 11 percent of the total tree biomass, but accumulated 21 percent of the total N, 27 percent of the total P, 19 percent of the total K, and 31 percent of the total Ca.

Total accumulation of these nutrients in lodgepole pine trees was in the order of N > Ca > K > P, although distributions varied according to tree component. When results were expressed as the content of each nutrient in a tree component as a percentage of the total tree burden of that nutrient, the following sequences became evident:

N and K -- stems > needles > branches, twigs, and cones

P -- stems > needles = branches, twigs, and cones

Ca -- stems > branches, twigs, and cones > needles

Having determined nutrient contents of lodgepole pine stands, it was possible to determine actual nutrient removals as well as potential removals under a variety of theoretical cutting regimes (Table 17). The actual tree biomass harvested and removed from the 1972 clearcut site was 65,633 kg/ha. This was calculated from Cook Lumber Company data for the net weights of the 24 truck loads of logs. These weights were converted to dry weight per unit area by employing the experimentally derived specific gravity value for the whole lodgepole pine tree stem of 0.363, and converting pounds to kilograms. "Merchantable" trees were considered to be those with a diameter of five inches (12.7 cm) or more. However, data from Table 17 indicate that only about 81 percent of the stem biomass of those trees 12.7 cm and larger was actually removed. If the objective had been to remove all stems one inch (2.5 cm) in diameter and larger, then the actual harvest biomass was about 72 percent of the total tree stem biomass on the site. The actual harvest biomass represented about 59 percent of a "whole tree" harvest, in which all branches and foliage would be removed along with tree stems (as in Boyle and Ek, 1972; Boyle, Phillips, and Ek, 1973).

The actual nutrient removals and those resulting from the hypothetical cutting regimes are summarized in Table 18. Nutrient quantities are based on biomass estimates and nutrient levels for lodgepole pine since no data were available for nutrient concentrations in the tissues of Engelmann spruce or subalpine fir (except for Daubenmire, 1953).

Table 17. Actual and potential harvest biomass of the 1972 clearcut site.

Species	Actual Harvest (kg/ha)	Potential Harvest (Kg/ha)		
		Stems ≥ 12.7 cm	All Stems ≥ 2.5 cm	"Whole Tree"
Lodgepole pine[1]		76,418.8	86,516.5	104,322.2
Engelmann spruce and subalpine fir[2]		5,039.2	5,315.2	6,436.0
All species	65,633.0	81,458.0	91,831.7	110,758.2

[1]Values from Table 15 and from original stand data.

[2]Stem biomass estimates derived using regression equation of Landis (1972) $\hat{Y} = 8.3868 + .04557\ D^2H$. Branch and foliage biomass estimates derived using the lodgepole pine models reported in Table 14.

Table 18. Actual and potential nutrient removals in lodgepole pine trees in the 1972 clearcut site.

Nutrient	Actual Harvest	Potential Harvest		
		Stems ≥ 12.7 cm	All Stems ≥ 2.5 cm	"Whole Tree" Harvest
	kg/ha			
N	72.2	84.1	95.2	188.3
P	5.1	6.0	6.7	16.1
K	27.2	31.7	35.9	66.5
Ca	49.2	57.3	64.9	120.7

Clearcutting the 1972 clearcut site and removing 65,633 kg/ha of tree stems amounted to the loss of 72.2 kg/ha of N, 5.1 kg/ha of P, 27.2 kg/ha of K, and 49.2 kg/ha of Ca. This represented about 38 percent of the total tree N, 32 percent of the total P, and 41 percent of total K and Ca. Thus, 62 percent of the total tree N was left on the site as foliage, branches, and the stems not removed. In addition, 68 percent of the P and 59 percent of the K and Ca in the total tree was left on the site as logging residues. If all stems 2.5 cm in diameter and larger were removed the quantities of nutrients lost would increase to 95.2 kg/ha of N, 6.7 kg/ha of P, 35.9 kg/ha of K, and 64.9 kg/ha of Ca. Harvesting tops (branches, twigs, cones, and needles) as well as boles would more than double the quantities of nutrients actually removed from the site (188.3 kg/ha of N, 16.1 kg/ha of P, 66.5 kg/ha of K, and 120.7 kg/ha of Ca).

Understory Vegetation

Biomass Determinations

The effect of clearcutting on understory vegetation biomass is summarized in Table 19. Data are presented for the three sites for two years: 1972, prior to clearcutting the 1972 clearcut site, and 1973, subsequent to clearcutting this site.

Herbaceous layer vegetation (predominantly *Vaccinium scoparium*) comprised 90 percent of the total understory vegetation in the 1972 clearcut site prior to clearcutting, with tree reproduction and shrubs accounting for the additional 10 percent (Table 19). Clearcutting of this site reduced the total understory biomass by 52 percent, from

Table 19. Effect of clearcutting on understory vegetation biomass in three lodgepole pine sites.

Component	Year	1972 Clearcut (kg/ha)	Forest Control (kg/ha)	1965 Clearcut (kg/ha)
Herbaceous layer	1972	823[1]	585	943
	1973	376[2]	600	985
Tree reproduction and shrubs	1972	49[1]	251	278
	1973	44[2]	235	290
Total understory biomass	1972	872[1]	836	1221
	1973	420[2]	835	1275

[1]Prior to clearcutting.

[2]Subsequent to clearcutting.

872 kg/ha to 420 kg/ha. The understory component with the largest biomass decrease in 1973 was the herbaceous layer, which declined by 54 percent (from 823 to 376 kg/ha). Tree reproduction and shrub biomass (subalpine fir, Engelmann spruce, lodgepole pine, and *Juniperus communis*), however, showed only a 10 percent decrease. This decrease in total understory vegetation biomass evidentally resulted from mechanical disruptions and site disturbances during logging operations (e.g., skidding logs off the site).

Understory vegetation biomass of the forest control site in 1972 (836 kg/ha) was similar to the 1972 clearcut understory biomass before cutting (872 kg/ha). Biomass estimates of the understory vegetation in the forest control site were also similar between years (836 kg/ha in 1972 and 835 kg/ha in 1973). The herbaceous layer (principally *V. scoparium*) comprised about 70 percent of the total understory biomass in this site.

In 1972, the 1965 clearcut understory biomass was greater than either the 1972 clearcut (29 percent greater) or the forest control (32 percent greater). Biomass estimates in 1973 indicated a difference of 204 and 53 percent than these two sites, respectively. The large difference in 1973 between the 1965 clearcut and the 1972 clearcut was due to the decrease in understory vegetation biomass by logging in the latter site. Understory vegetation biomass estimates for the 1965 clearcut site were similar between years (1221 kg/ha in 1972, 1275 kg/ha in 1973). In both years herbaceous layer vegetation (various herbaceous species and *V. scoparium*) accounted for 77 percent of the total understory vegetation biomass. Tree reproduction and shrubs

(lodgepole pine and *Rubus* sp.) accounted for 278 kg/ha in 1972 and 290 kg/ha in 1973.

If understory vegetation biomass in the 1972 clearcut following clearcutting (420 kg/ha) can be used as a baseline to estimate biomass levels in the 1965 clearcut after cutting, then there has been an increase of total understory biomass of 204 percent (to 855 kg/ha) during the eight years subsequent to clearcutting. This would represent a 162 percent increase in herbaceous layer biomass and an increase of 559 percent in tree reproduction and shrub biomass. This biomass increase could be important to the question of increased incorporation of nutrients into the developing biomass of successional species as a mechanism of reducing potential nutrient losses following clearcutting (Marks and Bormann, 1972).

Nutrient Analysis

The two understory vegetation components (herbaceous layer vegetation and tree reproduction and shrubs) were chemically analyzed in 1972 and 1973 for total N, P, K, and Ca to determine the possible role of successional species in utilizing the potentially greater availability of nutrients following clearcutting. Results are presented graphically in Figures 17-20 and in tabular form in Appendix C, Tables 2 and 3.

Figure 17 depicts percent total N in herbaceous layer vegetation and tree reproduction and shrubs in the three sites for the two subsequent years. The large differences between 1972 and 1973 values for the herbaceous vegetation can be probably attributed to the

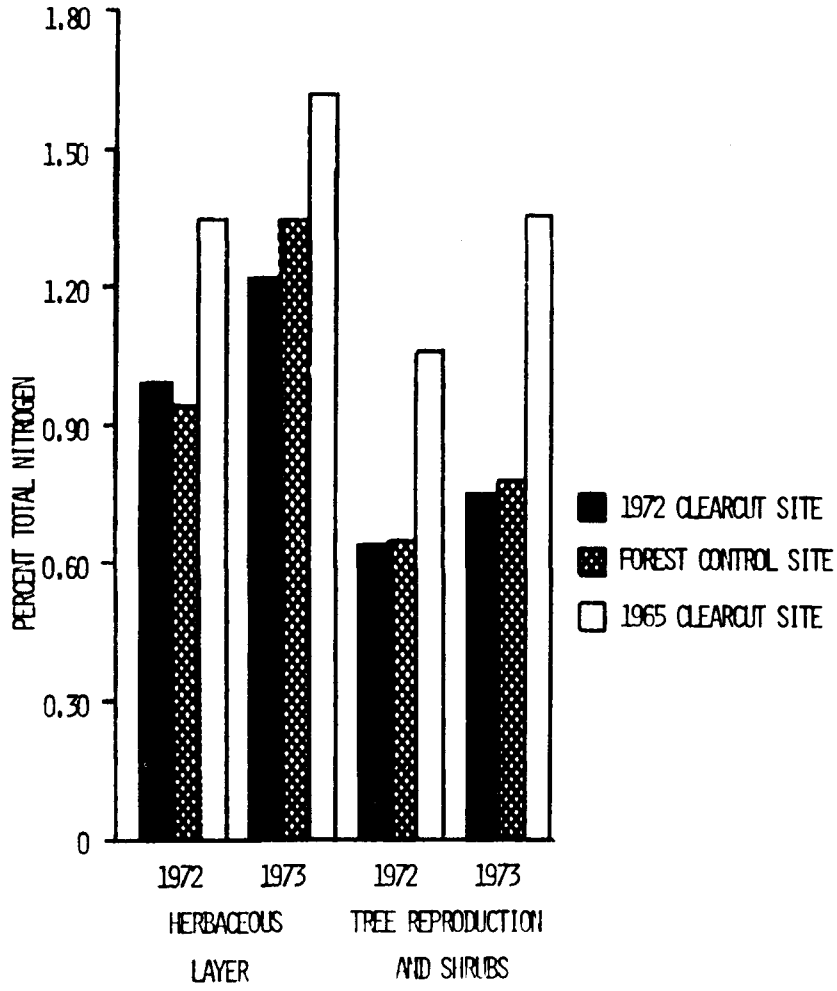


Figure 17. Percent total nitrogen of understory vegetation in three lodgepole pine sites for two subsequent years.

difference in sample size (n = 24 in 1972, n = 40 in 1973). Despite this annual variation, differences in levels of N were statistically significant. Levels of N in herbaceous layer vegetation were significantly higher in the 1965 clearcut as compared with the other two sites, at the $\alpha = 0.01$ level in 1972 and at the $\alpha = 0.10$ level in 1973. Levels of N in tree reproduction and shrubs from the 1965 clearcut were significantly higher at the $\alpha = 0.01$ level for both years. Ranges of total N in herbaceous layer vegetation were from 1.35 to 1.60 percent in the 1965 clearcut and from 0.94 to 1.37 percent in the other two sites. Shrubs and tree reproduction ranged from 1.06 to 1.36 percent N in the 1965 clearcut site, and ranged from 0.63 to 0.74 percent N in the 1972 clearcut and forest control sites.

Understory vegetation in the 1965 clearcut site also showed higher levels of total P, with significance levels of $\alpha = 0.01$ for both understory components and for both years (Figure 18 and Appendix C, Tables 2 and 3). Levels of P in the 1965 clearcut herbaceous layer ranged from 1700 to 1852 ppm during the two years, while P levels in the other two years ranged from 914 to 1161 ppm. Phosphorus in tree reproduction and shrubs from the 1965 clearcut ranged from 1293 to 1306 ppm, while corresponding vegetation in the other two sites had a range of 838 to 992 ppm.

Total K in the 1965 clearcut successional understory vegetation was also at significantly higher levels ($\alpha = 0.01$) during both years (Figure 19). The range of K in herbaceous layer vegetation from the 1965 clearcut was from 6709 to 10,139 ppm for both years, while the range in the other two sites was from 2332 to 3718 ppm K. Tree

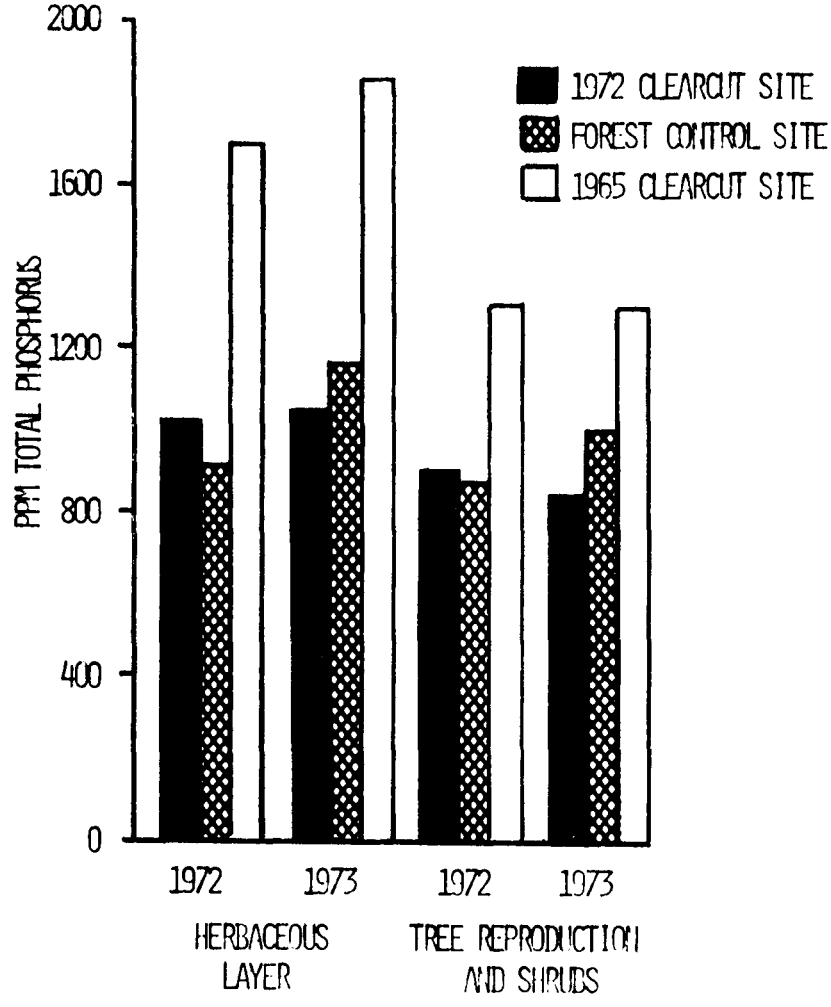


Figure 18. Parts per million total phosphorus of understory vegetation in three lodgepole pine sites for two subsequent years.

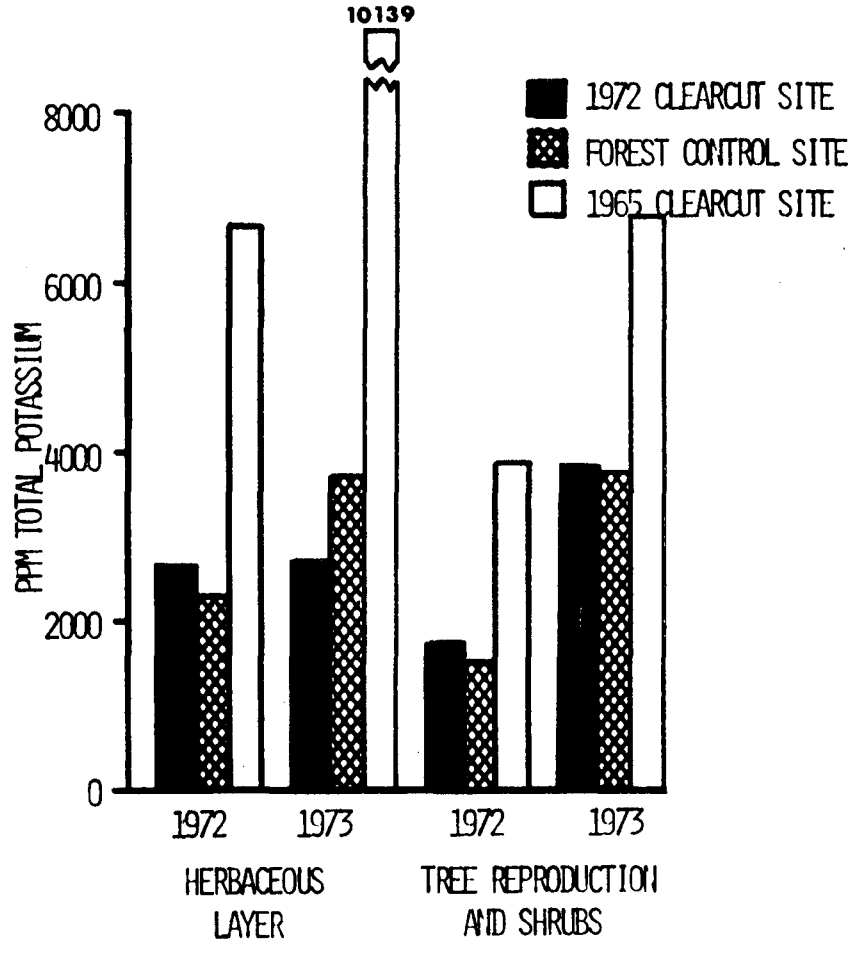


Figure 19. Parts per million total potassium of understory vegetation in three lodgepole pine sites for two subsequent years.

reproduction and shrubs ranged from 3903 to 6797 ppm K in the 1965 clearcut, and from 1538 to 3819 ppm K in the 1972 clearcut and forest control sites.

Total Ca did not show the same patterns of higher levels of accumulation in the 1965 clearcut understory vegetation as did total N, P, and K (Figure 20). While levels of Ca in herbaceous layer vegetation appeared to be similar in all three sites (ranging from 3554 to 5125 ppm), levels of Ca in tree reproduction and shrubs were significantly ($\alpha = 0.01$) lower in the 1965 clearcut site as compared with the other two sites (Appendix C, Tables 2 and 3).

At least two possibilities exist in attempting to explain the differences in levels of N, P, K, and Ca in understory vegetation between sites: (1) species differences between the 1965 clearcut site and the 1972 clearcut and forest control sites; or (2) an increased adaptive capacity of the same species to utilize the greater availability of nutrients in the 1965 clearcut site. In an attempt to discover an explanation to the problem of differential absorption of these nutrients, understory vegetation was separated and chemically analyzed by species in 1973. Results are presented in Table 20 (herbaceous layer vegetation), Table 21 (tree reproduction), and Table 22 (shrubs).

Table 20 summarizes means, standard deviations, and ranges of total N, P, K, and Ca of herbaceous layer vegetation by species in the three sites in 1973. *Vaccinium scoparium* was the only species common to all three sites, and appeared to have higher N, P, and K levels in the 1965 clearcut site than in either of the other two sites. There

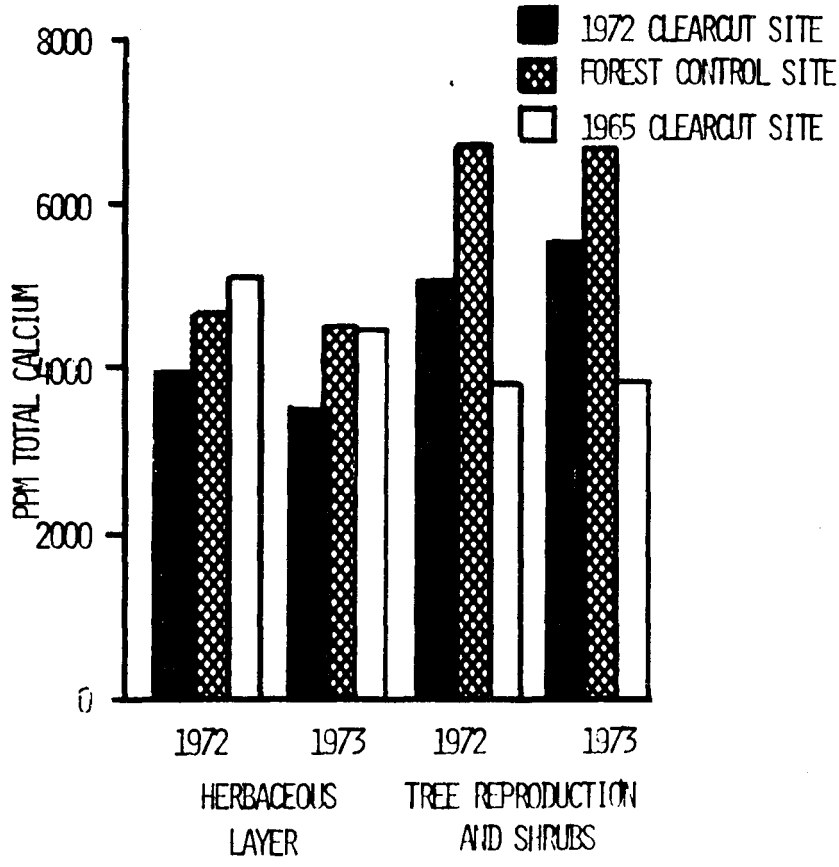


Figure 20. Parts per million total calcium of understory vegetation in three lodgepole pine sites for two subsequent years.

Table 20. Means, standard deviations, and ranges for total nitrogen, phosphorus, potassium, and calcium of herbaceous layer vegetation by species in 1973.

Site	Species	Nitrogen (percent)	Phosphorus (ppm)	Potassium (ppm)	Calcium (ppm)
1972 Clearcut[1]	*V. scoparium*	1.24±.18 (1.00-1.55)	1041±213 (750-1600)	2635±750 (1500-4500)	3554±762 (2250-5000)
Forest Control	*V. scoparium*	1.37±.22 (1.08-2.18)	1161±226 (625-1675)	3718±1016 (1750-5500)	4489±902 (2125-6000)
1965 Clearcut	*V. scoparium*	1.72±.20 (1.58-1.87)	2062±548 (1675-2450)	11750±10253 (4500-19000)	6000±1061 (5250-6750)
	A. cordifolia	2.25±.21 (2.10-2.40)	2188±972 (1500-2875)	14250±6718 (9500-19000)	5750±4419 (2625-8875)
	Lupinus sp.[2]	3.33	2925	16500	5250
	E. Angustifolium	2.01±.58 (1.41-2.77)	2569±1203 (1750-4350)	8938±1638 (7500-11000)	7550±2139 (6375-10750)
	Sedges + Grasses	1.32±.29 (0.86-2.14)	1572±415 (875-2300)	9417±3887 (3750-17250)	3440±749 (2375-5375)

[1]Subsequent to clearcutting.

[2]Sample size of 1.

appeared to be an increased adaptive capacity of this species to preferentially absorb and accumulate larger amounts of these nutrients. Levels of N concentrated in the tissues of *V. scoparium* in the 1965 clearcut site averaged 1.72 percent, but ranged from 1.24 to 1.37 in the other two sites. Phosphorus levels in this species were 2062 ppm in the 1965 clearcut, but were 1041 and 1161 ppm in the 1972 clearcut and forest control sites, respectively. Potassium was accumulated at particularly high levels by *V. scoparium* in the 1965 clearcut site (11,750 ppm) as compared with the 1972 clearcut (2635 ppm) and the forest control (3718 ppm) sites. Calcium levels in this species were not significantly different between sites (3554-6000 ppm). The successional species *Arnica cordifolia*, *Lupinus* sp., and *Epilobium angustifolium*, as well as grasses and sedges, which either occurred exclusively or in greater numbers in the 1965 clearcut site, also had higher total N, P, and K levels than the herbaceous layer vegetation in either the 1972 clearcut of forest control site (Table 20). Thus it appeared that both mechanisms postulated above for higher nutrient levels in 1965 clearcut herbaceous layer vegetation were operating.

Table 21 summarizes means, standard deviations, and ranges of total N, P, K, and Ca in tree reproduction by species in the three sites in 1973. Tree reproduction was further separated into the components of needles, stem and branches, and roots to give an indication of the distribution of these nutrients. Subalpine fir seedlings were sampled from both the 1972 clearcut and forest control sites, and total N, P, K, and Ca in the tree components appeared to be at similar levels in both sites. Lodgepole pine seedlings were sampled from the

Table 21. Means, standard deviations, and ranges for total nitrogen, phosphorus, potassium, and calcium of tree reproduction by species in 1973.

Site	Species	Tree Component	Nitrogen (percent)	Phosphorus (ppm)	Potassium (ppm)	Calcium (ppm)
1972 Clearcut[1]	*Abies lasiocarpa*	Needles	0.90±.32 (0.53-1.09)	1125[2]	3500[2]	7125[2]
		Stem and Branches	0.60±.25 (0.42-0.89)	862±407 (575-1150)	4375±1945 (3000-5750)	4812±1326 (3875-5750)
		Roots	0.36±.06 (0.32-0.40)	462±159 (350-575)	1875±177 (1750-2000)	2375±1237 (1500-3250)
Forest Control	*Pinus contorta*[2]	Needles	1.10	600	2000	2875
		Stem and Branches	0.43	375	1250	2375
	Abies lasiocarpa	Needles	1.10±.14 (0.92-1.35)	1225±123 (600-1350)	6089±5211 (2000-19750)	7389±1947 (2875-10750)
		Stem and Branches	0.50±.15 (0.23-0.79)	908±158 (700-1150)	4118±930 (2525-5250)	4975±1330 (3250-7000)
		Roots	0.31±.10 (0.23-0.47)	538±159 (350-800)	2129±883 (1000-3275)	2479±923 (1375-3625)
1965 Clearcut	*Pinus contorta*	Needles	1.47±.24 (1.00-1.97)	1120±197 (825-1500)	4148±1024 (2750-6000)	3080±1346 (1750-7125)
		Stem and Branches	0.65±.12 (0.52-0.90)	1069±145 (925-1375)	5825±1124 (4500-8750)	1490±1056 (750-4875)
		Roots	0.49±.14 (0.30-0.77)	1330±362 (750-1950)	6517±1876 (4000-10000)	1542± 878 (750-7750)

[1]Subsequent to clearcutting.
[2]Sample size of 1.

forest control site and from the 1965 clearcut, but it was difficult to make comparisons due to the sample size of one seedling from the forest control site. However, it appeared from the limited data that the lodgepole pine seedling components of needles and stem and branches from the 1965 clearcut had higher N, P, and K levels than either lodgepole pine or subalpine fir seedlings from the other two sites. On the other hand, when total Ca in tree reproduction components was compared between species, subalpine fir from the 1972 clearcut and forest control sites had higher Ca levels in needles, stem and branches, and roots. Daubenmire (1953) also found relatively high levels of Ca in subalpine fir needles as compared with lodgepole pine needles. Thus species composition differences between sites might explain in part the significantly higher levels of total N, P, and K, and lower levels of total Ca, in tree reproduction and shrubs in the 1965 clearcut as compared with the other two sites.

Nutrient levels in shrub species from the three sites in 1973 are summarized in Table 22. *Juniperus communis* was the only shrub species sampled from the 1972 clearcut and forest control. Species sampled from the 1965 clearcut were *Arctostaphyles uva-ursi*, *Rosa* sp., and *Rubus strigosus*. Total N, P, and K were at higher levels in shrubs from the 1965 clearcut site, particularly in *Rosa* sp. and *Rubus strigosus*, further explaining the higher levels of these nutrients in tree reproduction and shrubs from this site. On the other hand, *J. communis* had relatively high levels of total Ca in the 1972 clearcut (15,875 ppm) and the forest control (14,625 ppm) sites, which were higher than levels in *A. uva-ursi* (4875 ppm), *Rosa* sp. (8375 ppm) or *Rubus strigosus* (7589 ppm) from the 1965 clearcut site.

Table 22. Means, standard deviations, and ranges for total nitrogen, phosphorus, potassium, and calcium of shrubs by species in three lodgepole pine sites in 1973.

Site	Species	Nitrogen (percent)	Phosphorus (ppm)	Potassium (ppm)	Calcium (ppm)
1972 Clearcut[1]	*J. communis*[2]	0.70	500	3025	15,875
Forest Control	*J. communis*[2]	0.83	750	4000	14,625
1965 Clearcut	*A. uva-ursi*[2]	0.79	700	3500	4875
	Rosa sp.[2]	1.46	1500	8250	8375
	Rubus strigosus	2.36±0.93 (0.79-3.59)	2093±514 (700-2650)	12971±4236 (3500-16500)	7589±1463 (4875-10125)

[1]Subsequent to clearcutting.

[2]Sample size of 1.

Nutrient levels in understory vegetation had different proportional patterns according to site. Nutrient levels in the 1972 clearcut and forest control sites appeared to be in the order of N > Ca > K > P, while levels in the 1965 clearcut were in the order of N > K > Ca > P. This difference in relative ranking of these nutrients is due to the high levels of K found in herbaceous layer vegetation and tree reproduction and shrubs in the 1965 clearcut (Figure 19).

Nutrient Quantities

Distribution of the amounts of total N, P, K, and Ca between the herbaceous layer vegetation and tree reproduction and shrub components of understory vegetation in 1973 for the three sites on a kg/ha basis is summarized in Table 23. Herbaceous layer vegetation accounted for between 63 to 94 percent of the total amounts of nutrients in understory vegetation. Total amounts of nutrients accumulated in understory vegetation were greatest in the 1965 clearcut, due not only to higher nutrient levels, but also to the larger amounts of herbaceous layer and tree reproduction and shrub biomass in that site, as discussed earlier. Compared to the total nutrient amounts of understory vegetation in the 1972 clearcut and forest control sites respectively the 1965 clearcut site understory vegetation had 254 and 97 percent more N, 627 and 144 percent more P, 900 and 287 percent more K, and 267 and 28 percent more Ca (Table 23). The proportional trend of nutrient accumulation in understory vegetation in the 1972 clearcut and forest control sites was N > Ca = K > P, while the trend in the

Table 23. Distribution of nitrogen, phosphorus, potassium, and calcium between herbaceous layer vegetation and tree reproduction and shrub components of understory vegetation in 1973.

Site	Component	N		P		K		Ca	
		kg/ha	% total	kg/ha	% total	kg/ha	% total	kg/ha	% total
1972 Clearcut[1]	Herbaceous Layer Vegetation	.7	94.0	0.4	90.9	1.0	83.3	1.3	86.7
	Tree Reproduction and Shrubs	0.3	6.0	0.04	9.1	0.2	6.7	0.2	13.3
	Total	5.0	100.0	0.44	100.0	1.2	100.0	1.5	100.0
Forest Control	Herbaceous Layer Vegetation	8.2	82.0	0.7	77.8	2.2	71.0	2.7	62.8
	Tree Reproduction and Shrubs	1.8	18.0	0.2	22.2	0.9	29.0	1.6	37.2
	Total	10.0	100.0	0.9	100.0	3.1	100.0	4.3	100.0
1965 Clearcut	Herbaceous Layer Vegetation	15.8	80.2	1.8	81.8	10.0	83.3	4.4	80.0
	Tree Reproduction and Shrubs	3.9	19.8	0.4	18.2	2.0	16.7	1.1	20.0
	Total	19.7	100.0	2.2	100.0	12.0	100.0	5.5	100.0

[1]Subsequent to clearcutting.

1965 clearcut was N > K > Ca > P. This difference related to the higher levels of K in 1965 clearcut understory vegetation (Figure 19).

Logging Residues

Biomass Determinations

Biomass of slash components in the 1972 and 1965 clearcut sites is summarized in Table 24. Total amounts and relative proportions of the various components of logging residues differed between sites.

Total slash biomass of the 1965 clearcut (10,982.0 kg/ha) was about one-fourth that in the 1972 clearcut (42,484.5 kg/ha). Most of this biomass difference was due to the larger amounts of stems (484 percent greater biomass), branches (309 percent greater biomass), and needles (1222 percent greater biomass) in the 1972 clearcut. In contrast, the 1965 clearcut had a 56 percent greater twig biomass than the 1972 clearcut.

These logging residue biomass differences between sites could be a result of several factors. To begin with, the initial forest stand conditions before clearcutting might have been different (e.g., less tree stem density in the 1965 clearcut, resulting in a smaller slash biomass potential). Sampling of stumps in the 1965 clearcut might have given an indication of previous tree density. In addition, tree population characteristics in the 1972 clearcut (Figure 3) revealed a relatively large number of stems in the smaller d.b.h. classes, which were considered unmerchantable and left as logging residues.

The possibility of slash biomass decrease in the 1965 clearcut as a result of decomposition should not be overlooked. However, it was

Table 24. Biomass of logging residues by slash components in the 1972 and 1965 clearcut sites.

Component	1972 Clearcut		1965 Clearcut	
	kg/ha	% of Total	kg/ha	% of Total
Stems (>10 cm Dia.)	22,740.5	53.5	3,894.9	35.8
Branches[1] (1-10 cm Dia.)	16,424.7	38.7	4,012.5	36.8
Twigs (<1 cm Dia.)	1,841.3	4.3	2,872.8	26.4
Needles	1,478.0	3.5	111.8	1.0
Total Biomass	42,484.5	100.0	10,892.0	100.0

[1]Includes cones.

estimated by Stark (1973) that it requires six to eight years for the complete decomposition of a Jeffrey pine *(Pinus jeffreyi* "Oreg. Com.") needle, 36 years for the decay of branches with bark, and from 140 to 150 years for the complete decay of a log. The activity of decay fungi in logging residues is frequently limited by rapid and great fluctuations of temperature, which are usually concomitant with suboptimal moisture conditions (Dickinson and Pugh, 1974). Thus the seven years which elapsed between the clearcutting of this site and our sampling would probably not be sufficient to account for the difference in stem and branch biomass, but might be a factor in explaining the relatively small amounts of needle biomass in the 1965 clearcut.

Relative proportions of stem and branch biomass were similar in the 1965 clearcut (35.8 and 36.8 percent of the total, respectively). Stems in the 1972 clearcut accounted for 53.5 percent of the total biomass, and branches 38.7 percent. This would be further evidence of the greater number of stems left after harvesting the 1972 clearcut site. Twigs comprised 26.4 percent of the total biomass in the 1965 clearcut, but only 4.3 percent in the 1972 clearcut. The greater proportion of the smaller woody particles in the 1965 clearcut could be a result of fragmentation of larger branch materials by physical weathering, snow movements, wind, and animal movements (e.g., deer).

Foulger and Harris (1973) reported a total of 121,277.5 kg/ha of logging residues excluding needles after clearcutting a lodgepole pine stand in western Wyoming. Of this residue, 82.3 percent was more than 3.0 inches (7.6 cm) in diameter. This value appeared high compared to our data, but their technique did not separate live and dead material.

Our values were closer to those of Kiil (1967) who found 44,832.0 kg/ha of logging residues after clearcutting lodgepole pine in Alberta.

Nutrient Analysis

Slash from the two clearcut sites was chemically analyzed for total N, P, K, and Ca, and compared to determine nutrient quantities in nine-month-old logging residues from the 1972 clearcut, and seven-year-old residues from the 1965 clearcut. Results are presented graphically in Figures 21-24 and in tabular form in Appendix C, Table 4. For the most part, nutrient levels in slash components from the 1972 clearcut were similar to levels in corresponding lodgepole pine tree components (Appendix C, Table 1), while nutrient levels in the 1965 clearcut slash were dramatically lower.

Figure 21 depicts percent total N of the slash components of needles, twigs, branches, and stems in the two sites. Comparison of N levels between slash components of the two sites indicated significantly different concentrations, except for needles. Needles from slash in the 1972 clearcut had 0.88 percent N, while needles from the 1965 clearcut had 0.85 percent N. On the other hand, twigs showed a 45 percent difference in percent N, with levels of 0.38 and 0.21 percent in the two sites, respectively, which were significantly different at the $\alpha = 0.01$ level. Branches had N levels that were also 45 percent different, with values of 0.20 and 0.11 percent in the 1972 and 1965 clearcut sites, respectively, again significantly at the $\alpha = 0.01$ level. Stems showed only a 27 percent difference and significance at the $\alpha = 0.10$ level, with N levels of 0.11 percent in the 1972 clearcut and 0.08 percent in the 1965 clearcut (Appendix C, Table 4). It was

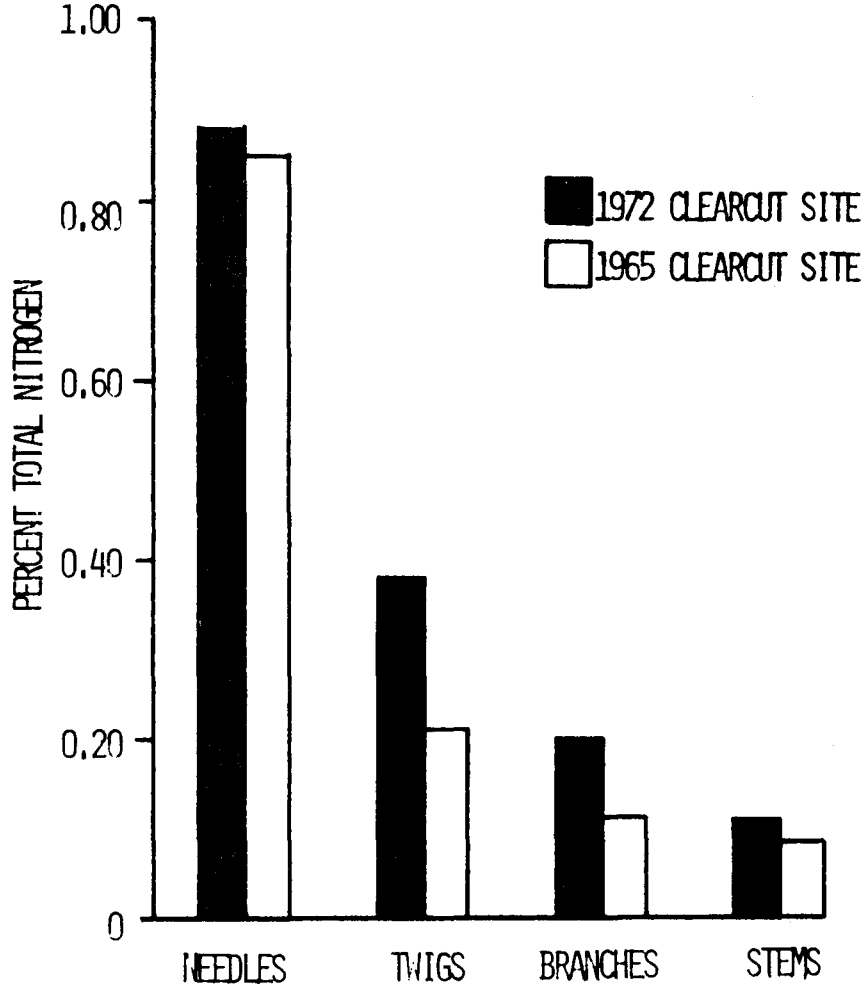


Figure 21. Percent total nitrogen of slash components in two lodgepole pine clearcuts of different ages.

unclear why needles and stems presumably had not lost much of their original N, while N levels in 1965 clearcut twigs and branches were about half the N levels in 1972 clearcut twigs and branches. Either there was very little N being lost in needles and stems, or slash-decomposing fungi in these materials were cycling and reusing substrate N during decay. Dickinson and Pugh (1974) reported that the wood-decomposing basidiomycetes are known to be able to utilize large amounts of carbohydrates and lignin in wood with relatively small amounts of N present, and re-use the N in their own mycelium, thereby conserving the small amounts of N in stem wood.

Figure 22 depicts ppm total P in logging residue components of the 1972 and 1965 clearcut. Levels of P in 1965 clearcut slash components were significantly lower than levels in 1972 clearcut slash at the $\alpha = 0.05$ level for needles and the $\alpha = 0.01$ level for twigs, branches, and stems. Needles had P levels of 867 ppm in the 1972 clearcut and 688 ppm in the 1965 clearcut. Levels of P in twigs were 290 and 210 ppm, in branches 155 and 130 ppm, and in stems 125 and 95 ppm in the two sites, respectively. Thus it appeared, if P levels in 1972 clearcut slash could be used as baseline values, that there had been a 21 percent decrease in needle P, and a 28, 16, and 24 percent decline in twig, branch, and stem P levels, respectively.

Seven-year-old slash evidentally has lost much of its original K (Figure 23). Levels of K in the 1965 clearcut logging residue components were all significantly lower at the $\alpha = 0.01$ level than levels in the 1972 clearcut slash components (Appendix C, Table 4). Potassium levels in the 1972 and 1965 clearcuts were 2133 and 766 ppm

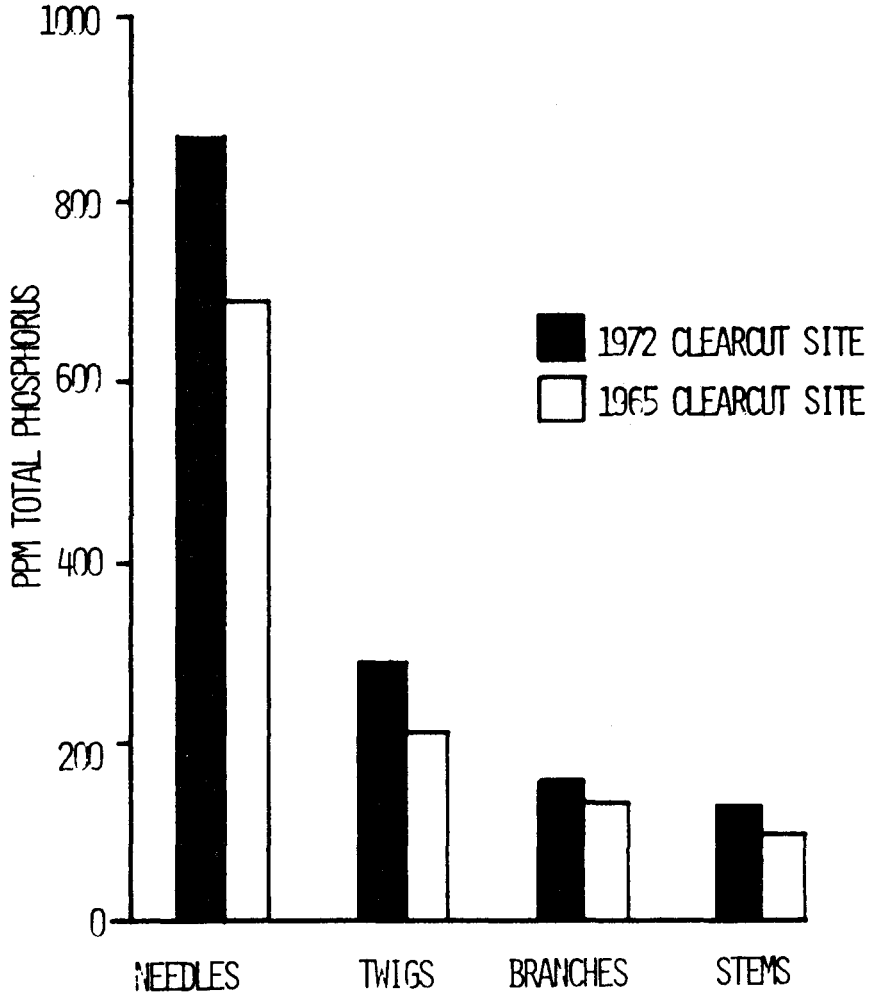


Figure 22. Parts per million total phosphorus of slash components in two lodgepole pine clearcuts of different ages.

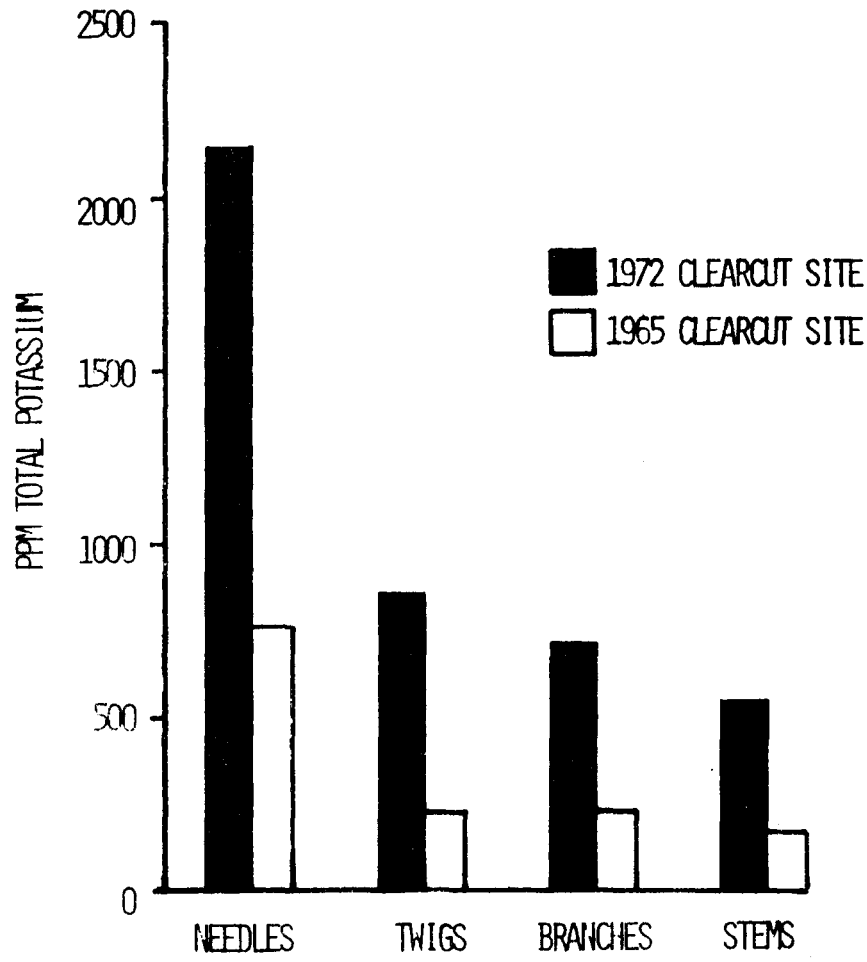


Figure 23. Parts per million total potassium of slash components in two lodgepole pine clearcuts of different ages.

for needles, 858 and 229 ppm for twigs, 715 and 229 ppm for branches, and 555 and 167 ppm for stems, respectively. Expressed as percentages, these differences represented a 64, 73, 68, and 70 percent reduction of needle, twig, branch, and stem K levels. Relatively rapid loss of K from logging residues would be expected, since K is highly soluble in biological systems and no organically bound forms are known.

Figure 24 depicts ppm total Ca of slash components in the two lodgepole pine clearcuts. Differences in levels of Ca between slash components of the two sites were much more extreme than for N, P, or K, and all differences were significant at the $\alpha = 0.01$ level. While needles of the 1972 clearcut slash had 2896 ppm of Ca, 1965 clearcut needle Ca levels were only 39 ppm, a reduction of 99 percent. Levels of Ca in twigs from slash of the two sites were 3112 ppm in the 1972 clearcut, and only 22 ppm in the 1965 clearcut (also a 99 percent decrease). Slash branches had 2300 ppm Ca in the 1972 clearcut and 15 ppm in the 1965 clearcut, again a 99 percent difference. Slash stems had 500 and 11 ppm Ca in the 1972 and 1965 clearcut sites, respectively, which represented a 98 percent difference. Evidently, Ca in the logging residues of the 1965 clearcut was being converted through the decay process to some readily soluble form which was being removed from the slash. The release of Ca from logging residues might explain the higher soil levels of Ca in the 1965 clearcut site as compared to the other two sites (Figure 9 and Appendix B, Table 6).

Nutrient Quantities

The distribution of amounts of total N, P, K, and Ca on a kg/ha basis between the slash components of the 1972 and 1965 clearcut is

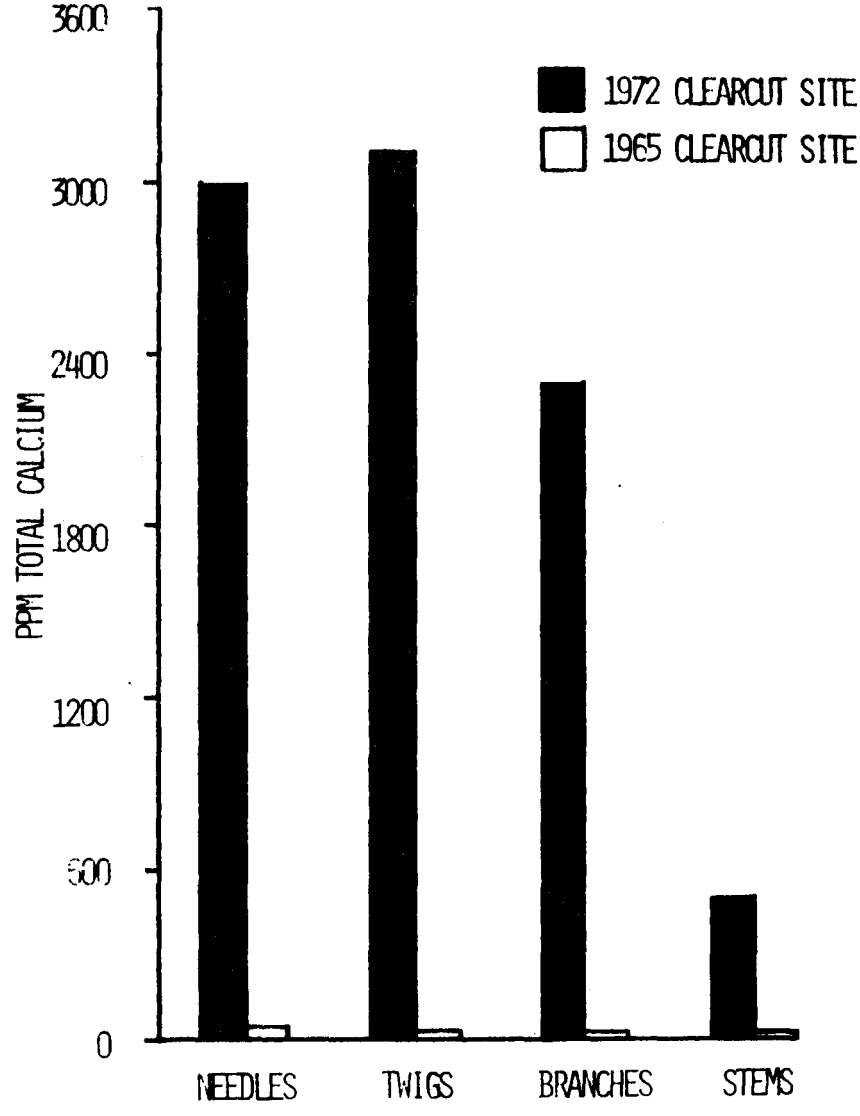


Figure 24. Parts per million total calcium of slash components in two lodgepole pine clearcuts of different ages.

summarized in Table 25. The differences in amounts of nutrients in logging residues between the two sites reflects not only the greater slash biomass in the 1972 clearcut, but also the higher nutrient levels of the logging residues in this site.

Total amounts of these nutrients in the logging residues from the 1972 clearcut were 826 percent greater than total amounts in the 1965 clearcut (173.2 kg/ha as compared with 18.7 kg/ha in the two sites, respectively).

While branches comprised about 39 percent of the total slash biomass in the 1972 clearcut, they accounted for 48.9 percent of the total nutrient quantities. In contrast, stems comprised about 54 percent of the total slash biomass of the 1972 clearcut, but accounted for only 29.9 percent of the total slash nutrients. Twigs accounted for about four percent of the total logging residue biomass and for 8.6 percent of the total nutrients. Needles also represented about four percent of the total slash biomass, but accounted for 12.6 percent of the total nutrients in logging residues from this site.

Stems, branches, and twigs had the highest nutrient quantities of the logging residue components in the 1965 clearcut site. Needles were insignificant in terms of nutrient quantities, due to the relatively small biomass of this slash component.

Overall Site Nutrient Budgets

Having established nutrient quantities in the lodgepole pine forest and clearcut ecosystem components of mineral soils, forest floors, lodgepole pine trees, understory vegetation, and logging

Table 25. Distribution of nitrogen, phosphorus, potassium, and calcium between the components of the 1972 and 1965 clearcut logging residues.

Site	Component	N		P		K		Ca	
		kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total
1972 Clearcut	Stems	25.0	32.1	2.8	39.5	12.6	43.3	11.4	19.3
	Branches	32.8	42.2	2.5	35.2	11.7	40.2	37.8	63.8
	Twigs	7.0	9.0	0.5	7.0	1.6	5.5	5.7	9.6
	Needles	13.0	16.7	1.3	18.3	3.2	11.0	4.3	7.3
	Total	77.8	100.0	7.1	100.0	29.1	100.0	59.2	100.0
1965 Clearcut	Stems	3.1	21.4	0.4	25.0	0.7	29.2	0.04	24.4
	Branches	4.4	30.3	0.5	31.2	0.9	37.5	0.06	36.6
	Twigs	6.0	41.4	0.6	37.5	0.7	29.2	0.06	36.6
	Needles	1.0	6.9	0.1	6.3	0.1	4.1	0.004	2.4
	Total	14.5	100.0	1.6	100.0	2.4	100.0	0.164	100.0

residues, it was possible to construct overall site nutrient budgets and to evaluate the effects of clearcutting on nutrient distribution within the three sites.

Table 26 summarizes the distribution of N, P, K, and Ca within the major ecosystem components of the undistrubed forest control site in 1973. By far, the greatest nutrient accumulation was in the mineral soil. Values for P, K, and Ca represented readily available forms of these nutrients in the top 30.5 cm of soil. Not included as part of the P, K, and Ca nutrient pool are those nutrients associated with the mineralogical structure of the soil system. The absence of data for mineralogical weathering represents a lack of information dealing with weathering rates in the central Rocky Mountains. Exchangeable amounts of K generally ranges between one to two percent of the total soil reserves of K, while exchangeable Ca usually represents from 20 to 40 percent of total soil Ca (Buckman and Brady, 1969). Nitrogen values represent total N which has been used extensively as an indication of the soil's ability to provide N for plant growth. Mineral soil in the forest control site accounted for 62.1 percent of the total ecosystem N, 74.0 percent of the "total" P, 71.1 percent of the "total" K, and 75.5 percent of the "total" Ca. "Total" ecosystem values for N, P, K, and Ca were based on total N but available P, K, and Ca in forest floor and mineral soil components (see footnotes 1 and 2 in Tables 26, 27, and 29).

The forest floor was also an important nutrient storage component of the forest ecosystem. The organic horizons of the forest floor contained 26.3 percent of the total ecosystem N. Thus the forest floor and underlying mineral soil accounted for 88.4 percent of the total

Table 26. Distribution of nitrogen, phosphorus, potassium, and calcium within the major ecosystem components of the forest control site in 1973.

Ecosystem Component	N		P		K		Ca	
	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total
Lodgepole Pine Trees[1]	183.0	11.0	15.6	20.4	64.6	20.8	117.1	13.1
Understory Vegetation[1]	10.0	0.6	0.9	1.2	3.1	1.0	4.3	0.5
Forest Floor[2]	436.8	26.3	3.4	4.4	22.0	7.1	96.7	10.9
Mineral Soil (30.5 cm)[2]	1030.6	62.1	56.6	74.0	221.2	71.1	673.6	75.5
Total	1660.4	100.0	76.5	100.0	310.9	100.0	891.7	100.0

[1]Nutrient values for lodgepole pine trees and understory vegetation represent totals for N, P, K, and Ca.

[2]Nutrient values for forest floor and mineral soil represent totals for N, available for P, and exchangeable for K and Ca.

ecosystem N. The forest floor also accumulated 4.4 percent of the "total" P, 7.1 percent of the "total" K, and 10.9 percent of the "total" Ca (Table 26).

The next most important ecosystem component of the forest control site in terms of nutrient accumulation was the forest overstory. Lodgepole pine trees accounted for 11.0 percent of the N, 20.4 percent of the P, 20.8 percent of the K, and 13.1 percent of the Ca. These values would be the nutrient loss expected if a "whole tree" harvest were used in this site. If a conventional clearcutting procedure were employed the percentages of these nutrients leaving the site would be less.

These data (Table 26) indicated that the understory vegetation was of minimal importance in the overall distribution of N, P, K, and Ca. The largest percentage accumulation was found for P (1.2 percent of the "total") and K (1.0 percent of the "total").

All ecosystem components accumulated nutrients in the order of N > Ca > K > P.

Table 27 summarizes the distribution of these nutrients within the major ecosystem components of the 1972 clearcut site in 1973 following clearcutting. Again, the greatest nutrient accumulations were in the mineral soil, which accounted for 60.7 percent of the total ecosystem N, 80.2 percent of the P, 72.8 percent of the K, and 80.0 percent of the "total" ecosystem Ca. The forest floor accumulated 33.4 percent of the N, 7.4 percent of the P, 14.0 percent of the K, and 12.5 percent of the Ca.

Again, subordinate vegetation was of minor importance in terms of nutrient accumulation. Logging residues, however, accounted for a

Table 27. Distribution of nitrogen, phosphorus, potassium, and calcium within the major ecosystem components of the 1972 clearcut site in 1973.

Ecosystem Component	N		P		K		Ca	
	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total
Logging Residues[1]	77.8	5.5	7.1	11.7	29.1	12.7	59.2	7.3
Understory Vegetation[1]	5.0	0.4	0.4	0.7	1.2	0.5	1.5	0.2
Forest Floor[2]	471.1	33.4	4.5	7.4	32.0	14.0	102.3	12.5
Mineral Soil (30.5 cm)[2]	856.0	60.7	48.6	80.2	166.8	72.8	651.9	80.0
Total	1409.9	100.0	60.6	100.0	229.1	100.0	814.9	100.0

[1]Nutrient values for logging residues and understory vegetation represent totals for N, P, K, and Ca.

[2]Nutrient values for forest floor and mineral soil represent totals for N, available for P, and exchangeable for K and Ca.

substantial quantity of the "total" site nutrients. These organic materials had nutrient accumulations accounting for 5.5 percent of the total site N, 11.7 percent of the "total" P, 12.7 percent of the "total" K, and 7.3 percent of the "total" Ca.

Clearcutting and removing the merchantable stems from this site in 1972 removed a certain proportion of nutrients from the site. When compared to the soil quantities of these nutrients, removals appeared to be minimal (Table 28). Expressed as a percentage of the nutrient reserves in the upper 30.5 cm of mineral soil, the actual harvest represented a loss of 8.4 percent of the soil N, 10.5 percent of the soil P, 16.3 percent of the soil K, and 7.6 percent of the soil Ca. These estimates of soil reserves of P, K, and Ca are probably quite conservative since they are based on extractable quantities. Thus, soil reserves of N appeared to be adequate for about 12, 200-year rotations of lodgepole pine, assuming no nutrient additions through mineral weathering, precipitation, biological fixation, and organic matter decomposition. Nutrients which appeared to be most rapidly depleted from available reserves in the 1972 clearcut were K and P (6 to 9 rotations). It appeared that soil reserves of Ca were enough to sustain 13 similar clearcutting rotations.

It is known that precipitation, mineral weathering, and organic matter mineralization are all positive sources of nutrient input in forest ecosystems. Supplements of nutrients from these sources would be expected to extend these estimates by several 200-year rotations. For example, Stottlemyer and Ralston (1970) found that 11.1 kg/ha/year of Na, K, Mg, and Ca combined was added in throughfall to a lodgepole

Table 28. Actual and potential nutrients removals in relation to soil nutrient reserves (30.5 cm) in the 1972 clearcut site.

Cutting Regime	Nitrogen kg/ha	% of Soil Reserves	Phosphorus kg/ha	% of Soil Reserves	Potassium kg/ha	% of Soil Reserves	Calcium kg/ha	% of Soil Reserves
Actual Harvest	72.2	8.4	5.1	10.5	27.2	16.3	49.2	7.6
Stem ≥ 12.7 cm	84.1	9.8	6.0	12.4	31.7	19.0	57.3	8.8
All Stems ≥ 2.5 cm	95.2	11.1	6.7	13.8	35.9	21.5	64.9	10.0
"Whole Tree" Harvest	188.3	22.0	16.0	32.9	66.5	39.9	120.8	18.5

pine forest ecosystem in the Fraser Experimental Forest in western Colorado. This would represent 2220 kg/ha of these nutrients added over a 200-year rotation. Woodmansee (1972) estimated inputs of K through precipitation to be 1.0 kg/ha/year, which would be 200 kg/ha over one rotation period of 200 years. Nitrogen reserves in the soil will be supplemented by a mineralization rate of from 2 to 3 percent per year (Buchman and Brady, 1969), or from 1884 to 2826 kg/ha over the 200 year rotation. In addition, N will be added in precipitation in amounts ranging from 3.6 to 7.4 kg/ha/year (720 to 1480 kg/ha for 200 years) according to Buchman and Brady (1969).

Table 28 also summarizes nutrient removals in relation to soil nutrient reserves under a variety of hypothetical cutting regimes. Using a "whole tree" harvesting technique, where tops as well as boles would be removed would more than double the quantities of nutrients removed from the site. Under this type of cutting regime, soil nutrient reserves would only be adequate for 2 to 5 rotations.

The distribution of nitrogen, phosphorus, potassium and calcium within the major ecosystem components of the 1965 clearcut site is indicated in Table 29. The mineral soil accounts for an even greater proportion of the total nutrient amounts accumulated in this site, primarily due to the lack of forest overstory, and the relatively low nutrient amounts in logging residues. Nutrients in mineral soils accounted for 70.9 percent of the total site N, 84.0 percent of the "total" P, 83.0 percent of the "total" K, and 89.2 percent of the "total" Ca. The one major difference in mineral soil nutrient quantities between the 1965 clearcut and the other two sites was the larger amounts of Ca accumulated (824.4 kg/ha as compared with 673.6 kg/ha in the forest

Table 29. Distribution of nitrogen, phosphorus, potassium, and calcium within the major ecosystem components of the 1965 clearcut site.

Ecosystem Component	N		P		K		Ca	
	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total	kg/ha	% of Total
Logging Residues[1]	14.5	1.1	1.6	4.1	2.4	1.2	0.2	0.02
Understory Vegetation[1]	19.7	1.4	2.2	5.7	12.0	5.9	5.5	0.6
Forest Floor[2]	363.4	26.6	2.4	6.2	20.1	9.9	94.6	10.2
Mineral Soil (30.5 cm)[2]	971.2	70.9	32.7	84.0	169.1	83.0	824.4	89.2
Total	1368.8	100.0	38.9	100.0	203.6	100.0	924.7	100.0

[1]Nutrient values for logging residues and understory vegetation represent totals for N, P, K, and Ca.

[2]Nutrient values for forest floor and mineral soil represent totals for N, available for P, and exchangeable for K and Ca.

control and 651.9 kg/ha in the 1972 clearcut sites). Otherwise amounts of nutrients in mineral soils appeared to be similar in the three sites, with the possible exception of P, which appeared to be accumulated in lesser quantities in the 1965 clearcut site (32.7 kg/ha as compared to 56.6 kg/ha in the forest control and 48.6 kg/ha in the 1972 clearcut sites).

Organic horizons accounted for 26.6 percent of the total site N, 6.2 percent of the P, 9.9 percent of the K, and 10.2 percent of the "total" Ca. Amounts of nutrients accumulated in the forest floor horizons of the three sites were similar.

Understory vegetation was more important in terms of the overall distribution of these nutrients in the 1965 clearcut, although accumulations were still quite low in relation to the total site quantities. The subordinate vegetation accounted for 1.4 percent of the total N, 5.7 percent of the "total" P, 5.9 percent of the "total" K, and 0.6 percent of the "total" Ca. In relation to understory vegetation in the other two sites, the subordinate vegetation in the 1965 clearcut site accumulated from two to nine times the amounts of N, P, K, and Ca. Thus, although the actual amounts of nutrients incorporated into the tissues of understory vegetation in the 1965 clearcut appeared to be small, they may be important in terms of reducing potential nutrient losses following clearcutting.

Logging residues in the 1965 clearcut had lost much of their original nutrient contents (Figures 21-24 and Appendix C, Table 4), and accounted for only 1.1 percent of the total site N, 4.1 percent of the P, 1.2 percent of the K, and 0.02 percent of the Ca.

Water--Quantity and Quality Determinations

Results

Definitions

Throughout the remainder of the text several terms will be employed for which definitions are necessary. Tube-tension lysimeters at depths of 75 to 100 cm will be referred to as "deep" lysimeters while "shallow" lysimeters will refer to tube-tension lysimeters at a depth of 50 cm. Plate lysimeters will refer to plate-tension lysimeters at a depth of 10 cm. Weekly mean concentrations are calculated by summing all individual concentrations from "deep" lysimeters from a treatment for a given sampling period and dividing by the number of individual samples analysed. Grand mean concentrations were calculated in a similar manner for the entire yearly sampling period. Weekly mean volumes were calculated by summing all water collected by "deep" lysimeters from a treatment for a given sampling period and dividing by sixteen, the number of "deep" lysimeters on each treatment. Grand mean volumes were calculated by summing all water collected from "deep" lysimeters during the yearly sampling period and dividing by the total number of individual lysimeter sample collections during the period (usually sixteen per week). Finally, solutes collected by an average lysimeter are referred to as being lost. This terminology is used because it is assumed that solutes in soil-water below the rooting zone represent losses from the system above, and eventually, additions to groundwater and/or streams.

Water

Grand mean water volumes during the 1973 sampling period were highest from the 1972 clearcut (188 ml), intermediate from the 1965 clearcut (161 ml), and lowest from the control (101 ml) (Table 30).

The control treatment exhibited the greatest range in weekly means for both sampling years. From a mean weekly high of 216 ml in early June, 1973, the mean volume decreased to 94 ml in mid-July, increased to 166 ml a week later and then rapidly decreased to zero in early September. Collections in early October showed an increase to 72 ml (Figure 25).

The weekly mean volume from the 1972 clearcut decreased from 181 ml in early June, 1973, to 141 ml by the end of June. Volumes then increased and remained fairly constant for about one month from July 21 to August 17, then decreased to a low in early September of 135 ml and then increased sharply to 228 ml in October. (Figure 25).

The 1965 clearcut exhibited a pattern that was almost identical to the other two treatments during 1973 but with intermediate volumes (about 30 ml less than the 1972 clearcut).

Weekly mean volumes during 1974 were slightly greater than for the same period in 1973 (Table 31). Water volumes were not recorded during 1974 before June 17.

Grand mean water volumes collected from the 1972 and 1965 clearcuts for the 1973 period were approximately 86 percent and 59 percent greater, respectively, than from the control (Table 30). In 1974, the grand mean volumes were about 38 percent and 20 percent greater than from the control for the 1972 and 1965 clearcuts, respectively (Table 31).

The weather station at Red Feather Lakes recorded over three inches of precipitation for the period from July 12-22, 1973 (U. S. Weather Bureau). In addition, 0.55 inches were recorded on August 1, 1973, and 0.72, 1.17, and 0.25 inches on September 11, 25, and 28, 1973, respectively. Significant precipitation events during the 1974 sampling period included a snow on June 8 with a water equivalent of 2.46 inches and a rain on June 18 of 0.40 inches.

Table 30. Weekly and grand mean* water volumes (ml) from "deep" lysimeters° during 1973.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.1/	N2/	Mean	S.E.	N	Mean	S.E.	N
6-06-73	216	32.2	7	181	26.4	16	144	22.2	16
6-15-73	133	23.5	12	156	21.8	16	137	23.1	16
6-22-73	182	20.0	16	178	21.7	16	150	15.0	16
6-29-73	98	17.0	16	141	18.0	16	90	12.7	16
7-06-73	107	17.2	16	146	19.3	16	156	27.9	16
7-13-73	94	16.6	16	157	21.0	16	132	26.0	16
7-21-73	166	27.3	16	216	24.5	16	197	25.8	16
7-27-73	142	24.9	16	229	22.7	16	199	28.8	16
8-03-73	146	25.3	16	213	22.0	16	180	29.1	16
8-09-73	110	23.9	16	212	22.0	16	182	27.5	16
8-17-73	48	16.8	16	234	24.3	16	203	34.7	16
8-24-73	23	10.5	16	177	20.1	16	187	28.5	16
9-07-73	0	0.0	16	135	26.2	16	86	24.6	16
10-03-73	48	25.9	16	210	20.7	16	169	31.4	16
10-10-73	72	28.9	16	228	15.2	16	207	26.0	16
Grand Mean	101	6.5	227	188	5.8	240	161	6.9	240

* Total water collected from a specific treatment during a sampling period divided by the number of "deep" lysimeters serviced during that period.

° Tube tension lysimeters at depths from 75 to 100 cm.

1/ Standard error of the mean

2/ Number of lysimeters serviced.

Table 31. Weekly and grand mean* water volumes (ml) from "deep" lysimeters° during 1974.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.1/	N 2/	Mean	S.E.	N	Mean	S.E.	N
6-24-74	218	19.5	16	221	21.6	16	200	22.8	16
7-03-74	179	21.6	16	204	22.6	16	183	25.4	16
7-09-74	126	19.1	16	170	23.2	16	168	23.8	16
7-16-74	102	22.1	16	186	20.5	16	155	24.2	16
7-23-74	91	24.6	16	203	18.4	16	155	24.0	16
Grand mean	143	10.8	80	197	9.4	80	172	10.6	80

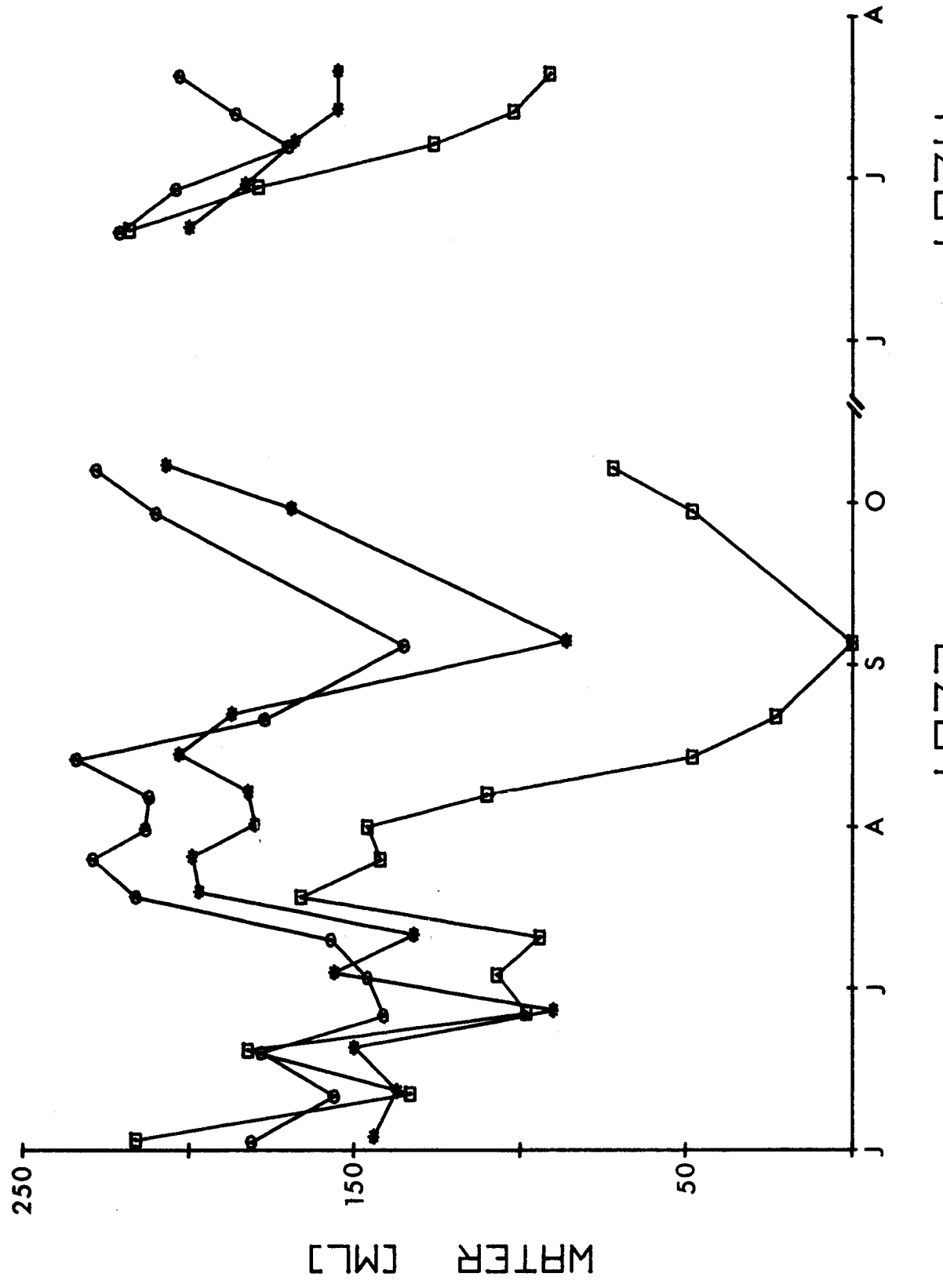
* Total water collected from a specific treatment during a sampling period divided by the number of "deep" lysimeters serviced during that period.

° Tube-tension lysimeters at depths from 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of lysimeters serviced.

Figure 25. Weekly mean water volumes from "deep" lysimeters (75 - 100 cm) during 1973 and 1974. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.


WATER [ML]
250
150
50
J
A
S
O
J
J
A
1974
1973

Nitrate

Grand mean nitrate concentrations for the 1973 period were 0.43, 0.77, and 3.49 mg/l for the control, 1972 clearcut, and 1965 clearcut, respectively (Table 32). The 1972 clearcut grand mean concentration was 79.1 percent greater than the control while the 1965 clearcut was 711.1 percent greater than the control. For the period of measurements in 1974, grand mean nitrate concentrations were 0.29, 3.42, and 2.24 mg/l for the control, 1972 and 1965 clearcuts, respectively (Table 33). The 1972 clearcut was 1079.3 percent greater than the control during 1974 while the 1965 clearcut was 672.4 percent greater than the control.

For the period from June 6 to July 21, 1973, and from June 3 to July 23, 1974, mean nitrate concentrations were 0.47 and 0.27 mg/l for the control, 0.50 and 3.35 mg/l for the 1972 clearcut, and 2.96 and 2.06 for the 1965 clearcut, respectively. These values represent an average decrease of 42.6 percent for the control in 1974, an average decrease of 30.4 percent for the 1965 clearcut, and an average increase of 570 percent for the 1972 clearcut.

Weekly mean concentrations from the control were amazingly constant during both years (Figure 26). With the exception of the June 15, 1973, sample, weekly mean concentration from the control ranged from 0.11 to 0.50 mg/l in 1973 and 0.15 to 0.40 mg/l in 1974.

Individual sample maximums from the control were 1.68 mg/l (July 13 1973) and 0.84 mg/l (July 17, 1974). A maximum of 6.16 mg/l was obtained on June 15, 1973. The mean weekly concentrations from the control and the 1965 clearcut for this date appear to be inconsistent with subsequent results. It is possible that samples were incorrectly

labeled on this date. The values were not changed, however, and appear in grand mean calculations for the appropriate treatments.

A preliminary sampling in late October, 1972, yielded a mean nitrate concentration from the control of 0.57 mg/l for four samples.

Nitrate concentrations from the 1965 clearcut exhibited the greatest weekly mean values and weekly variation during 1973. After an initial decrease from 2.39 mg/l on June 6, 1973 the weekly mean concentration gradually increased through mid-July to 5.00 mg/l. The mean concentration then decreased to 3.28 mg/l in mid-August. By the October 3 sample the mean concentration had increased sharply to a season high of 6.66 mg/l and with the final sample on October 10 had decreased to 4.60 mg/l.

During 1974, the 1965 clearcut, except for two occasions, had lower mean concentrations than the 1972 clearcut but were still higher than those from the control. From an initial weekly mean concentration of 3.58 mg/l in late May, the concentration decreased to a low of 1.14 mg/l in late June and then increased to 2.50 mg/l in mid-July. A slight decrease to 2.09 mg/l was noted with the final sample on July 23, 1974.

The preliminary sampling in late October, 1972, from the 1965 clearcut resulted in a mean nitrate concentration of 3.06 mg/l for eight samples.

Individual samples maximums from the 1965 clearcut were 28.19 mg/l (October 3, 1973) and 18.24 mg/l (May 27, 1974).

Differences in nitrate concentrations between the two years were the most dramatic from the 1972 clearcut. Preliminary samples in late October, 1972 (immediately after clearcutting),yielded a mean nitrate concentration of 0.37 mg/l from three samples.

Table 32. Weekly and grand mean nitrate concentrations (mg/l) in soil-water samples from "deep" lysimeters° during 1973.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
6-06-73	.30	.70	6	.35	.08	13	2.39	.73	12
6-15-73	1.56	.63	9	.45	.05	13	.77	.47	12
6-22-73	.15	.05	14	.62	.28	13	2.51	.64	14
6-29-73	.38	.06	11	.51	.10	13	2.39	.66	13
7-06-73	.35	.05	10	.53	.09	13	3.21	1.06	11
7-13-73	.37	.13	12	.50	.14	13	4.69	2.38	10
7-21-73	.42	.06	12	.58	.10	13	5.00	1.28	13
7-27-73	.50	.09	11	.88	.23	14	3.82	1.22	13
8-03-73	.27	.07	12	.60	.17	14	3.38	1.07	11
8-17-73	.11	.05	5	.66	.35	15	3.28	.99	11
10-03-73	.41	.18	3	2.30	1.70	15	6.66	2.61	11
10-10-73	.29	.10	6	1.10	.41	12	4.60	2.63	9
Grand mean	.43	.06	111	.77	.17	161	3.49	.38	140

° Tube-tension lysimeters at depths from 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analysed.

Table 33. Weekly and grand mean nitrate concentrations (mg/l) in soil-water samples from "deep" lysimeters° during 1974.

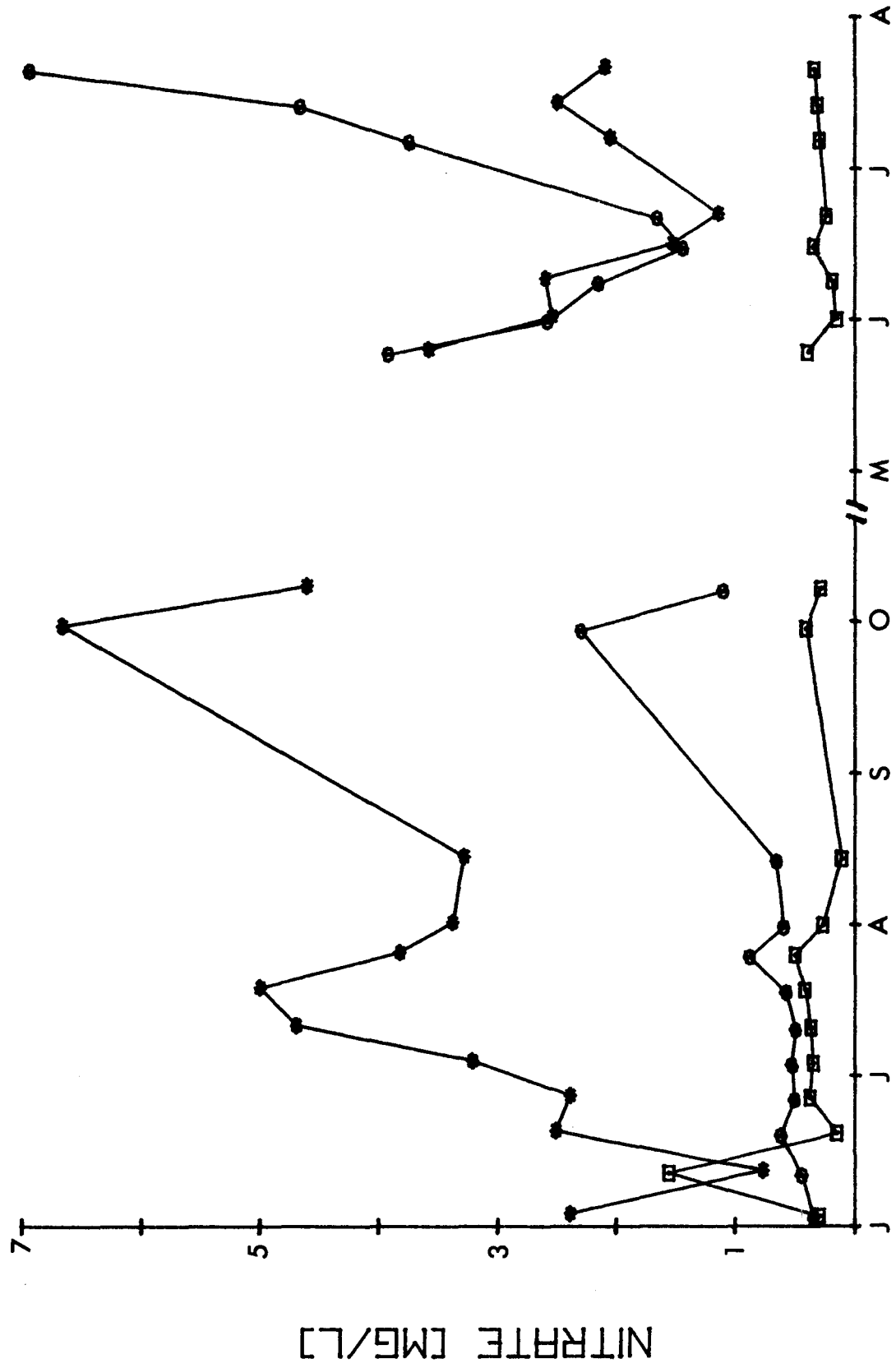
Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
5-27-74	.40	.07	11	3.92	2.28	14	3.58	1.59	13
6-03-74	.15	.05	11	2.58	.99	15	2.54	.85	14
6-12-74	.19	.05	12	2.15	.89	15	2.60	.79	14
6-17-74	.35	.06	15	1.44	.65	15	1.53	.52	15
6-24-74	.24	.05	15	1.66	.78	14	1.14	.48	14
7-09-74	.30	.05	14	3.74	1.42	14	2.05	.61	14
7-16-74	.32	.06	12	4.66	1.91	15	2.50	.69	13
7-23-74	.34	.06	11	6.93	3.45	15	2.09	.72	13
Grand mean	.29	.02	101	3.42	.64	117	2.24	.29	110

° Tube-tension lysimeters at depths from 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analysed.

Figure 26. Weekly mean nitrate concentrations from "deep" lysimeters (75 - 100cm) during 1973 and 1974. Squares, circles, and asterisks represent the control, the 1972, and the 1965 clearcuts, respectively. Means are located at the mid-point of a sampling period.


NITRATE [MG/L]
7
5
3
1
J
A
S
O
N
D
J
F
M
A
1973
1974

Weekly mean concentrations from the 1972 clearcut were always greater than the control during 1973 (except for the June 15 sample) and less than the 1965 clearcut. By mid-August, weekly mean concentrations from the 1972 clearcut began to diverge from the control, reaching a 1973 maximum for the treatment of 2.30 mg/l on October 3. The final sample in 1973 showed a decrease to 1.10 mg/l.

On May 27, 1974, the 1972 clearcut weekly mean concentration was 3.92 mg/l. The weekly mean concentration decreased to 1.44 mg/l in mid-June and then increased sharply to a two-year high of 6.93 mg/l on July 23, 1974.

A 1973 individual sample maximum from the 1972 clearcut of 26.42 mg/l occurred on October 3, while for 1974, an individual sample maximum of 51.21 mg/l was obtained on July 23, from the same "deep" lysimeter. After analysis revealed this extremely high concentration, the "deep" lysimeter was replaced with a new tube lysimeter. The following week (July 29, 1974) a concentration of 54.89 mg/l was obtained from the new lysimeter. The porcelin cup from the original lysimeter was allowed to soak in distilled water for one week after it was removed from the ground. Analysis of the water after soaking yielded a concentration of only 0.21 mg/l probably indicating no nitrate production within the lysimeter.

An insufficient number of samples from the plate and "shallow" lysimeters, due to low soil moisture, precluded any statistical analyses for these collections. Results that we were able to obtain are presented in Table 34. It appears that for both years, the concentrations obtained at 10 cm were greater than those from deeper depths from the control, about the same as those at deeper depths from the 1972 clearcut, and lower than the deeper lysimeter concen-

Table 34. Mean nitrate concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973 and 1974.

		Treatment								
		Control			1972 Clearcut			1965 Clearcut		
Sampling Date	Depth	Mean	S.E.1/	N2/	Mean	S.E.	N	Mean	S.E.	N
6-06-73	10	---	---	-	---	---	-	2.09	.90	4
	50	.52	.06	5	.41	.12	5	8.28	4.88	6
6-15-73	10	---	---	-	.40	---	1	2.11	---	1
	50	2.62	1.14	5	.70	.13	6	.62	.58	3
6-22-73	10	1.22	---	1	.21	.15	2	.70	---	1
	50	.22	.07	7	.69	.27	7	1.57	.82	5
6-29-73	50	.44	.08	5	.71	.29	4	3.44	2.72	2
7-06-73	10	---	---	-	.48	---	1	1.97	.25	2
	50	.44	.09	3	.88	.30	5	9.34	---	1
7-13-73	50	.33	.23	2	.88	.29	5	---	---	-
7-21-73	10	2.91	1.03	2	---	---	-	2.57	.44	3
	50	.56	.10	7	.94	.32	6	4.15	2.76	6
8-03-73	50	.32	.10	6	.87	.29	6	8.18	5.80	4
8-17-73	50	.24	.17	3	.53	.22	5	17.84	13.54	2

(continued)

Table 34. (continued)

Sampling Date	Depth	Treatment: Control Mean	Control S.E.	Control N	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
5-27-74	10	---	---	-	1.13	---	1	---	---	-
	50	---	---	-	1.44	.42	3	5.35	5.07	3
6-03-74	10	---	---	-	1.92	.92	2	---	---	-
	50	.36	---	1	1.14	.30	3	.29	.15	3
6-12-74	10	1.96	---	1	---	---	-	1.17	---	1
	50	.29	---	1	1.46	.73	4	1.12	.79	4

1/ Standard error of the mean.
2/ Number of samples analysed.

trations from the 1965 clearcut. The concentrations from the "shallow" (50 cm) lysimeters were consistent with those at deeper depths from all three treatments.

Comparisons between treatment grand means for 1973 using all individual samples from "deep" lysimeters showed the 1965 clearcut nitrate levels to be significantly greater than either the 1972 clearcut or the control at an alpha level of 0.005. There was no significant difference between grand mean concentrations from the 1972 clearcut and the control in 1973.

Comparisons of 1974 samples showed the grand mean concentration from the 1972 clearcut to be significantly greater than the control and the 1965 clearcut at alpha levels of 0.005 and 0.250, respectively. The 1965 clearcut was significantly greater than the control at an alpha level of 0.025. Analysis of variance results are presented in Appendix E, Table 1.

Weekly and grand totals of nitrate collected by an average "deep" lysimeter were calculated for both sampling years (Tables 35,36). During the sampling period of 1973 a grand total of 7.3 mg/ADL (average "deep" lysimeter) were lost from the 1965 clearcut, 1.9 mg/ADL from the 1972 clearcut, and 0.6 mg/ADL from the control. The 1965 clearcut lost over eleven times more nitrate than the control during the period in 1973 while the 1972 clearcut lost almost three times more than the control.

During the 1974 period, grand totals of 0.3, 5.0, and 2.8 milligrams of nitrate were collected by an average lysimeter from the control, 1972, and 1965 clearcuts, respectively. The amount of nitrate collected from the 1972 clearcut was almost 15 times greater than that from the control and about twice as great as that from the 1965 clearcut during 1974.

Table 35. Nitrate (mg) collected by an average "deep" lysimeter* during 1973.

Sampling Date	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06-73	.065	.063	.344
6-15-73	.207	.070	.150
6-22-73	.027	.110	.379
6-29-73	.037	.072	.215
7-06-73	.037	.077	.501
7-13-73	.035	.078	.619
7-21-73	.070	.216	.985
7-27-73	.071	.202	.760
8-03-73	.039	.130	.608
8-17-73	.005	.154	.666
10-03-73	.027	.483	1.126
10-10-73	.021	.251	.952
Grand Total	.641	1.906	7.302

* Tube-tension lysimeters at depths of 75 to 100 cm.

Table 36. Nitrate (mg) collected by an average "deep" lysimeter* during 1974.

Sampling Date	Treatment		
	Control	1972 Clearcut	1965 Clearcut
5-27-74°	.069	.674	.516
6-03-74°	.026	.444	.366
6-12-74°	.033	.370	.374
6-17-74°	.060	.278	.220
6-24-74	.052	.367	.228
7-09-74	.038	.636	.344
7-16-74	.033	.867	.388
7-23-74	.029	1.407	.324
Grand Total	.340	5.043	2.760

* Tube-tension lysimeters at depths of 75 to 100 cm.

° Mean water volumes of 172, 172, and 144 ml applied to the Control, 1972 Clearcut, and 1965 Clearcut, respectively. These volumes are the average for the period from 6-06-73 to 6-22-73 from the appropriate treatment. Water volumes were not recorded for this period in 1974.

Ammonium

For the period of sampling in 1973, grand mean ammonium concentrations were 0.12 mg/1 for the control, 0.07 mg/1 for the 1972 clearcut, and 0.06 mg/1 for the 1965 clearcut (Table 37). Based on these grand mean concentrations, 1972 and 1965 clearcut means were almost 42 and 50 percent less than the control.

The control, except on two occasions, exhibited greater weekly mean concentrations, and on all occasions exhibited greater variability than either of the two clearcuts (Table 37),(Figure 27). From an initial mean concentration of 0.12 mg/1 in early June, the mean weekly concentration decreased to 0.09 mg/1 by mid-June, and then increased to 0.19 mg/1 in late June. This rise was followed by a decrease to a season low of 0.08 mg/1 in late July and a subsequent sharp increase to a season high of 0.30 mg/1 on August 17. An individual sample maximum of 0.91 mg/1 was recorded on August 17. Analyses were not conducted for ammonium prior to the 1973 samples.

Weekly mean concentrations from both the 1972 and 1965 clearcuts followed a pattern similar to the control, although concentrations were lower. Ranges from both clearcuts were between 0.04 and 0.09 mg/1. Individual sample maximums were 0.20 mg/1 (June 22) for the 1972 clearcut and 0.34 mg/1 (July 21) for the 1965.

Concentration data from "shallow" and plate lysimeters are tabulated in Appendix D, Table 1.

Comparisons between grand mean ammonium concentrations showed the control to be significantly greater than either clearcut treatment at an alpha level of.005. There was no significant differences between grand mean concentrations from the two clearcuts. Analysis of variance results are contained in Appendix E, Table 2.

Table 37. Weekly and grand mean ammonium concentrations (mg/l) in soil-water samples from "deep"* lysimeters during 1973.

Sampling Date	Treatment								
	Control			1972 Cleacut			1965 Clearcut		
	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
6-06-73	0.12	0.06	6	0.06	0.02	13	0.04	0.01	12
6-15-73	0.09	0.03	9	0.04	0.01	13	0.07	0.01	12
6-22-73	0.11	0.05	14	0.05	0.02	13	0.04	0.02	14
6-29-73	0.19	0.07	11	0.08	0.02	13	0.09	0.02	11
7-06-73	0.10	0.04	10	0.05	0.02	13	0.06	0.02	11
7-13-73	0.08	0.03	11	0.08	0.01	13	0.06	0.02	10
7-21-73	0.08	0.04	7	0.06	0.01	10	0.08	0.03	9
8-17-73	0.30	0.17	5	0.09	0.02	10	0.06	0.04	8
Grand mean	0.12	0.02	73	0.07	0.005	98	0.06	0.008	87

* Tube-tension lysimeters at depths from 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 27. Weekly mean ammonium concentrations from "deep" lysimeters (75 - 100 cm) during 1973. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.

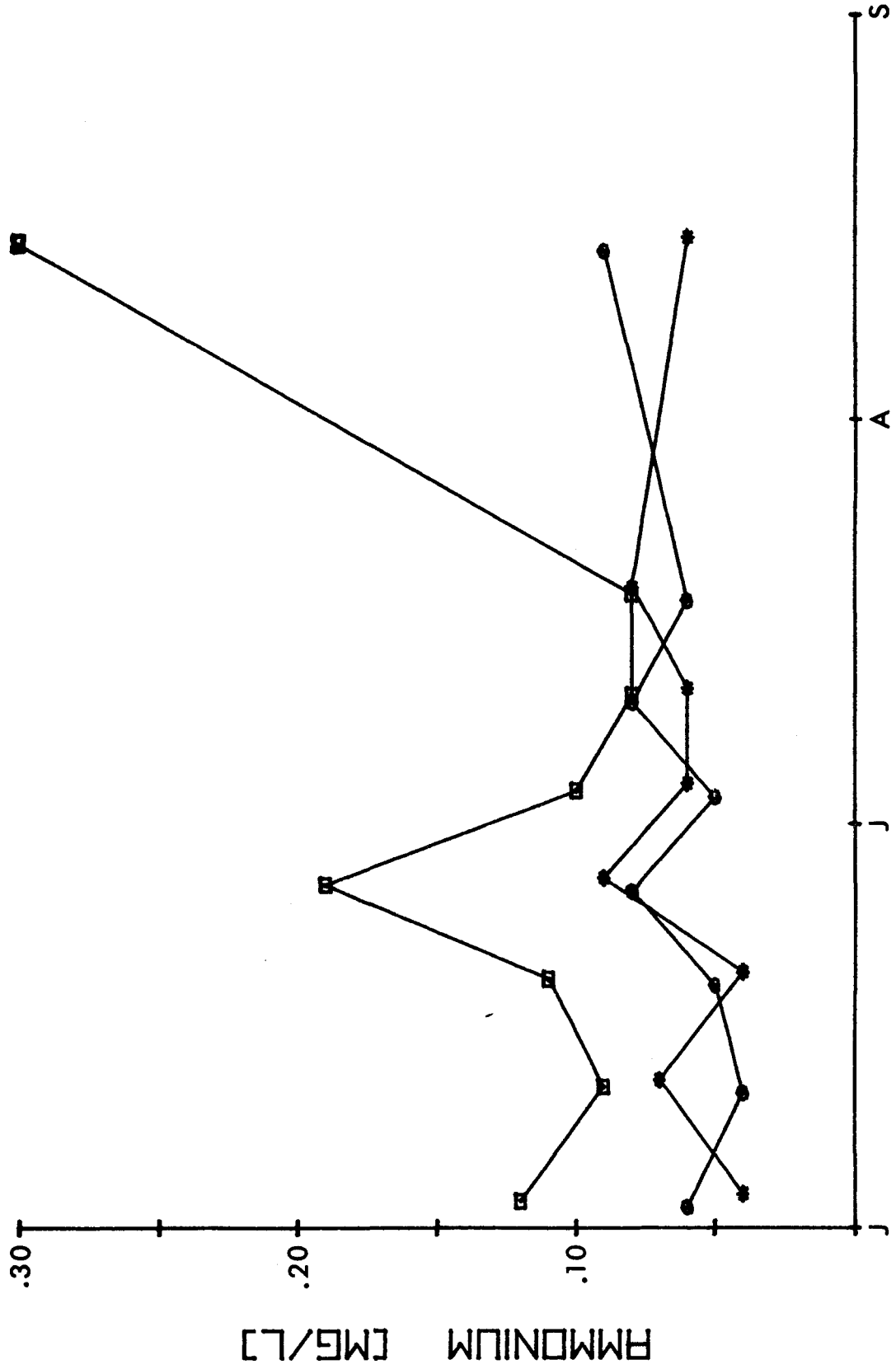


FIG 1

Total milligrams of ammonium collected by average "deep" lysimeters for the 1973 period were 0.12, 0.09, and 0.07 from the control, 1972, and 1965 clearcuts, respectively (Table 38). Total ammonium collected from the 1972 and 1965 clearcuts was about 24 and 40 percent less, respectively, than from the control. Ammonium totals were equivalent to 0.10, 0.08, and 0.06 mg of nitrogen for the control, 1972, and 1965 clearcuts, respectively.

Calcium

Calcium grand mean concentrations for the 1973 sampling period were 4.0, 6.3, and 6.0 mg/1 for the control, 1972 clearcut, and 1965 clearcut respectively (Table 39). During the period in 1974, grand mean concentrations were 2.6 mg/1 for the control, 5.0 mg/1 for the 1972 clearcut, and 3.3 mg/1 for the 1965 clearcut (Table 40). The 1972 and 1965 clearcut mean concentrations were 57.5 and 50.0 percent greater, respectively, than the control in 1973, while in 1974, grand mean concentrations were approximately 93 and 27 percent greater, respectively, than the control.

The control always exhibited lower weekly mean concentrations during both years (Figure 28). From a mean concentration of 5.3 mg/1 in early June, 1973, the weekly mean concentration from the control decreased sharply to 2.6 mg/1 near the first of July. From this 1973 season low, the values gradually increased to a season high of 6.1 mg/1 in early October. The weekly mean concentrations in 1974 gradually decreased from 3.1 mg/1 in late May to 2.3 mg/1 in late June when analyses were terminated.

Table 38. Ammonium collected (mg) by an average "deep"* lysimeter during 1973.

Sampling Date	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06-73	.026	.011	.006
6-15-73	.012	.006	.009
6-22-73	.019	.008	.006
6-29-73	.018	.011	.008
7-06-73	.011	.008	.009
7-13-73	.007	.013	.007
7-21-73	.013	.014	.016
8-17-73	.014	.020	.011
Grand Total	.120	.091	.072

*Tube-tension lysimeters at depths of 75 to 100 cm.

Individual sample maximums from the control were 12.0 mg/l on October 3 + 10, 1973, and 7.0 mg/l on May 27, 1974.

The 1965 clearcut exhibited a trend similar to the control during both years. The notable exception was a peak in early July 1973, of 7.0 mg/l. From a 1973 season high of 9.6 mg/l in early June, mean weekly concentrations from the 1965 clearcut decreased sharply in late June, increased sharply in early July to 7.0 mg/l, then decreased, increased, and finally decreased again to 6.2 mg/l in early October. During 1974, the concentrations followed those of the control but were approximately 0.5 to 1.5 mg/l greater.

Individual sample maximums from the 1965 clearcut were 20.0 mg/l on August 17 + 24, 1973, and 15.0 mg/l on May 27, 1974.

Weekly mean concentrations from the 1972 clearcut followed patterns similar to those from the 1965 clearcut. With the exceptions of the peak in early July, 1973, occurring approximately two weeks later and no decrease in early October, the patterns are almost identical. The weekly mean concentrations from the 1972 clearcut decreased from 8.2 mg/l in early June, 1973, to 2.8 mg/l in early July, increased to 7.9 mg/l two weeks later, then decreased to 5.6 mg/l in early August, and then rose gradually to 8.4 mg/l in early October. During 1974, weekly mean concentrations decreased from 7.1 mg/l in late May to 3.7 mg/l in early July. Concentration data from "shallow" and plate lysimeters are tabulated in Appendix D, Table 2.

Comparisons between grand mean concentrations from the three treatments during 1973 showed the two clearcuts to be significantly greater than the control at an alpha level of 0.005. There was no significant difference between grand mean concentrations from the two clearcuts during 1973. For the 1974 period, the grand mean concentration from the 1972 clearcut was significantly greater than either the control or the 1965 clearcut at an

Table 39. Weekly and grand mean calcium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	5.3	1.05	9	8.2	1.47	15	9.6	1.14	14
6-22 + 29-73	2.6	.54	14	4.4	.37	14	2.8	.39	16
7-06 + 13-73	2.6	.58	13	2.8	.41	14	7.0	.83	12
7-21 + 27-73	3.6	.72	13	7.9	.66	14	4.9	.54	15
8-03 + 09-73	4.3	.47	13	5.6	.48	14	5.6	.39	14
8-17 + 24-73	5.1	.77	10	6.2	.38	16	6.9	1.10	14
10-03 + 10-73	6.1	1.00	9	8.4	.93	16	6.2	.44	12
Grand mean	4.0	.29	81	6.3	.34	103	6.0	.34	97

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Table 40. Weekly and grand mean calcium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1974.

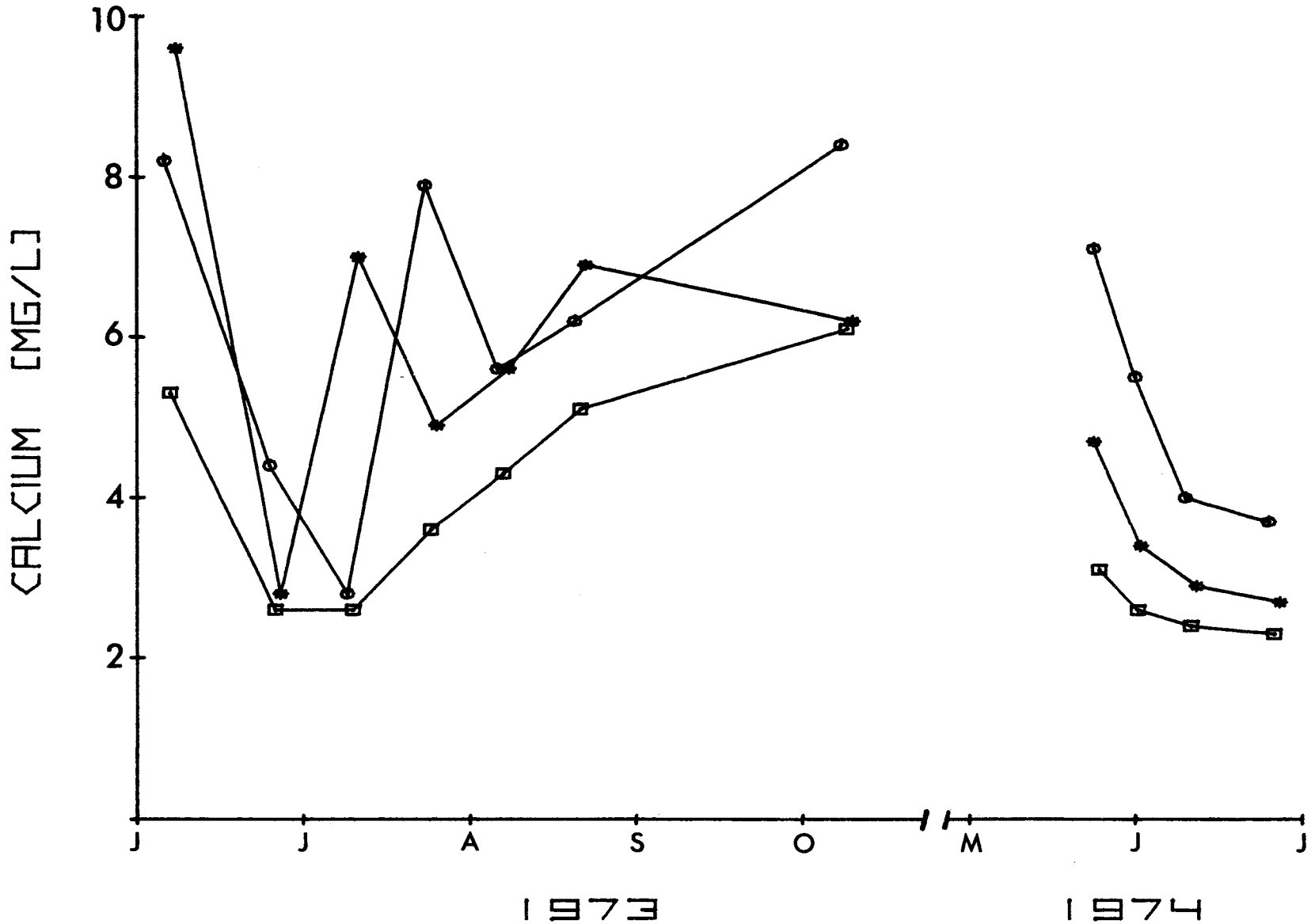
Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
5-27-74	3.1	.50	10	7.1	1.43	14	4.7	1.11	12
6-03-74	2.6	.30	11	5.5	.75	15	3.4	.30	14
6-12 + 17-74	2.4	.16	15	4.0	.61	16	2.9	.37	16
6-24 + 7-03-74	2.3	.13	15	3.7	.33	15	2.7	.26	15
Grand mean	2.6	.13	51	5.0	.44	60	3.3	.29	57

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 28. Weekly mean calcium concentrations from "deep" lysimeters (75 - 100 cm) during 1973 and 1974. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.


CALCIUM [MG/L]
10
8
6
4
2
J
J
A
S
O
M
J
J
1973
1974

alpha level of 0.005. Grand mean concentrations from the control and the 1965 clearcut during the 1974 period were not significantly different at an alpha level of 0.250. Analysis of variance results are contained in Appendix E, Table 3.

Total milligrams of calcium collected from average lysimeters during 1973 were 6.4, 17.1, and 14.4 from the control, 1972 clearcut, and 1965 clearcut, respectively (Table 41). The total from the 1972 clearcut was 167 percent greater than that from the control while the 1965 clearcut was 124 percent greater than from the control.

Magnesium

Grand mean magnesium concentrations were 1.1 mg/1 for all three treatments during the 1973 sampling period (Table 42). For the 1974 sampling period, grand mean concentrations were 0.7 mg/1 from the control, 1.3 mg/1 from the 1972 clearcut, and 1.1 mg/1 from the 1965 clearcut (Table 43). Results of magnesium analyses were reported to the nearest milligram per liter during 1974. Several values were reported as less than one mg/1. If an even number of these values occured from a treatment on a given sampling date, half were assumed to be 1 mg/1 and the other half 0 mg/1. If an odd number of these values occured, one values was assumed to be 0.5 mg/1. Treatment of the 1974 results in this manner allowed for maximum variation within the samples. Values are reported to the nearest 0.1 mg/1 in Tables 42 and 43 for both years.

Differences in weekly mean magnesium concentrations between the three treatments were not great during 1973 (Figure 29). The control decreased from an initial weekly mean concentration of 2.3 mg/1 to a low of 0.4 mg/1 in early July. The remaining samples showed a slow increase in mean concentrations to a late season plateau of about 1.4 mg/1.

Table 41. Calcium collected (mg) by average "deep" lysimeter* during 1973

Sampling Dates	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06 + 15-73	1.850	2.762	2.695
6-22 + 29-73	.730	1.400	.673
7-06 + 13-73	.523	.846	2.019
7-21 + 27-73	1.111	3.516	1.942
8-03 + 09-73	1.102	2.380	2.030
8-17 + 24-73	.362	2.548	2.691
10-03 + 10-73	.736	3.680	2.329
Grand Total	6.414	17.132	14.379

*Tube-tension lysimeters at depths of 75 to 100 cm.

Table 42. Weekly and grand mean magnesium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	2.3	1.10	9	1.3	.20	15	1.1	.12	14
6-22 + 29-73	1.1	.26	14	.6	.09	14	.6	.06	16
7-06 + 13-73	.4	.06	13	.5	.06	14	1.5	.45	12
7-21 + 27-73	.8	.08	13	.9	.08	14	1.2	.07	15
8-03 + 09-73	1.0	.24	13	1.2	.09	14	1.2	.08	14
8-17 + 24-73	1.3	.33	10	1.3	.07	16	1.2	.16	14
10-03 + 10-73	1.4	.12	9	1.8	.18	16	1.3	.13	12
Grand mean	1.1	.15	81	1.1	.06	103	1.1	.06	97

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Table 43. Weekly and grand mean magnesium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1974.

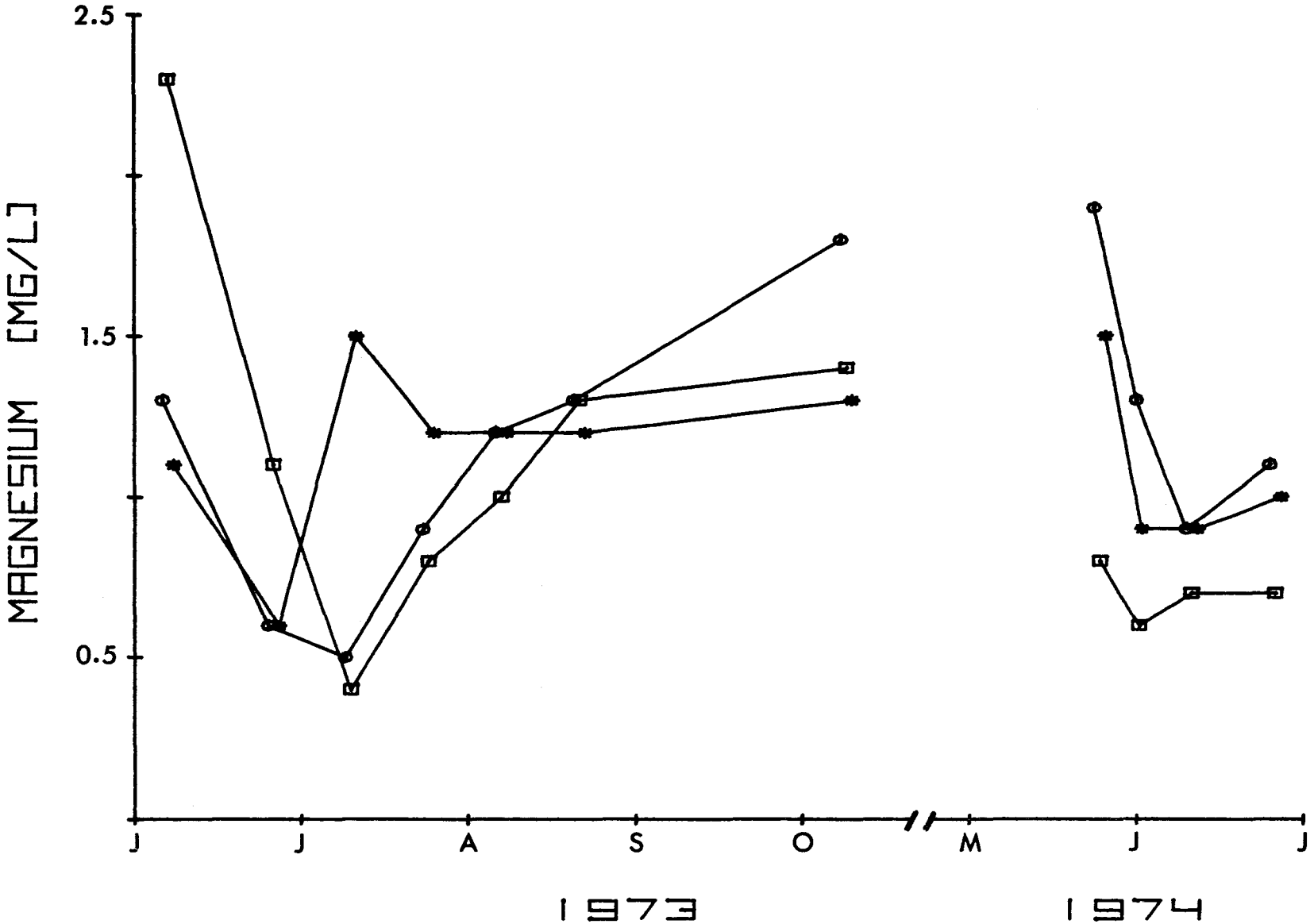
Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
5-27-74	.8	.11	10	1.9	.33	14	1.5	.37	12
6-03-74	.6	.15	11	1.3	.17	15	.9	.08	14
6-12 + 17-74	.7	.12	15	.9	.07	15	.9	.11	16
6-24 + 7-03-74	.7	.12	15	1.1	.12	15	1.0	.17	15
Grand mean	.7	.06	51	1.3	.10	59	1.1	.10	57

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 29. Weekly mean magnesium concentrations from "deep" lysimeters (75 - 100 cm) during 1973 and 1974. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.


MAGNESIUM [MG/L]
2.5
1.5
0.5
J
J
A
S
O
M
J
J
1973
1974

During 1973, the 1965 clearcut weekly mean concentration decreased from 1.1 mg/l in early June to 0.6 mg/l in late June. The concentration then increased to a season high of 1.5 mg/l in early July and then decreased and remained constant at approximately 1.2 mg/l for the remainder of the sampling period.

In 1973, the weekly mean concentration from the 1972 clearcut decreased from an initial value of 1.3 mg/l to 0.5 mg/l in early July. This was followed by a gradual rise during the rest of the season to a high of 1.9 mg/l in early October.

The control weekly mean concentration remained almost constant at 0.7 mg/l during 1974 while the two clearcuts decreased from around 1.7 mg/l to about 1.0 mg/l in early June and remained at this level throughout June.

Weekly mean magnesium concentrations from the "shallow" and plate lysimeters are tabulated in Appendix D, Table 3.

No significant differences were detected between treatment grand mean concentrations for the 1973 period. For the period of 1974, the 1972 clearcut and the 1965 clearcut grand mean concentrations were significantly greater than the control at alpha levels of 0.005 and 0.025, respectively. Grand mean concentrations from the two clearcuts were not significantly different during 1974. Analysis of variance results are contained in Appendix E, Table 4.

Total milligrams of magnesium collected by average lysimeters during 1973 were 1.96 from the control, 3.01 from the 1972 clearcut, and 2.75 from the 1965 clearcut (Table 44). Total amounts collected from the 1972 and 1965 clearcuts were 54 and 41 percent greater than from the control during the 1973 sampling period.

Table 45. Weekly and grand mean potassium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	1.0	.15	9	.6	.10	15	1.8	.27	14
6-22 + 29-73	1.9	.56	14	1.4	.18	14	1.9	.26	16
7-06 + 13-73	1.4	.14	13	2.1	.41	14	1.8	.25	13
7-21 + 29-73	1.1	.09	13	1.4	.15	14	1.6	.17	14
8-03 + 09-73	1.2	.09	13	1.5	.17	14	1.4	.10	14
8-17 + 24-73	1.6	.31	10	1.6	.12	16	1.6	.14	14
10-03 + 10-73	.9	.11	9	1.4	.11	16	1.1	.10	12
Grand mean	1.3	.11	81	1.4	.08	103	1.6	.08	97

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Table 46. Weekly and grand mean potassium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1974.

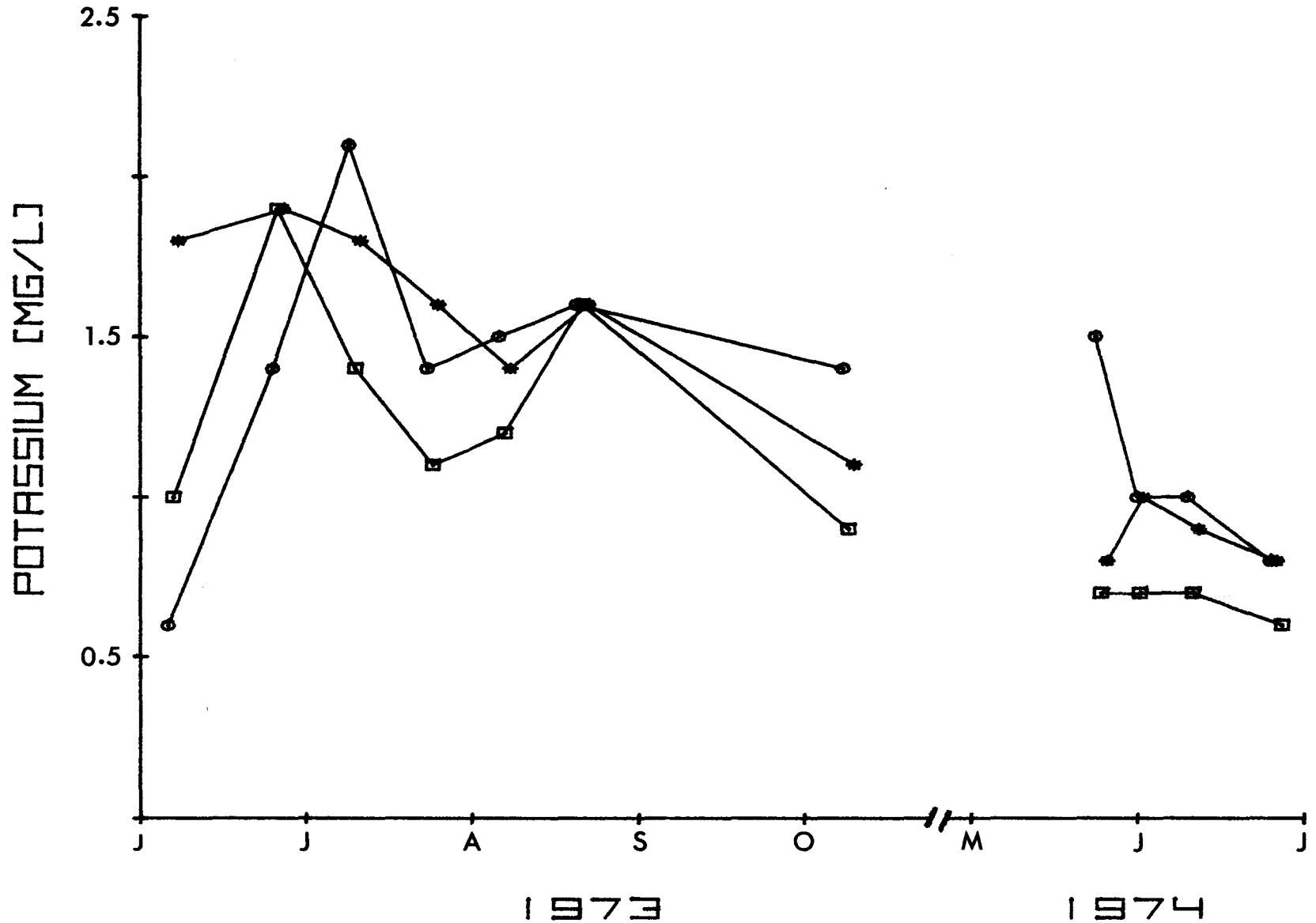
Sampling date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
5-27-74	.7	.15	10	1.5	.18	14	.8	.11	12
6-03-74	.7	.14	11	1.0	.12	15	1.0	.04	14
6-12 + 17-74	.7	.12	15	1.0	.15	16	.9	.11	16
6-24 + 7-03-74	.6	.12	15	.8	.14	15	.8	.09	15
Grand mean	.7	.06	51	1.1	.07	60	.9	.04	57

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 30. Weekly mean potassium concentrations from "deep" lysimeters (75 - 100 cm) during 1973 and 1974. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.


2.5
1.5
0.5
POTASSIUM [MG/L]
J
J
A
S
O
M
J
J
1973
1974

During 1974, the mean concentration decreased from 1.5 mg/1 in late May to about 1.0 mg/1 throughout June.

Potassium data from "shallow" and plate lysimeters are tabulated in Appendix D, Table 4.

Comparisons between grand mean treatment concentrations from 1973 resulted in only one significant contrast. The 1965 clearcut was greater than the control at an alpha level of 0.250. For the 1974 period, the grand mean concentrations from the 1972 clearcut was significantly greater than the control and the 1965 clearcut at alpha levels of 0.005 and 0.050, respectively. The 1965 clearcut was greater than the control at an alpha level of 0.100 for the 1974 period. Analysis of variance results are contained in Appendix E, Table 5.

Total milligrams of potassium collected by average lysimeters during 1973 were 2.0, 3.8, and 3.6 from the control, 1972, and 1965 clearcuts, respectively (Table 47). This represents an increased loss of potassium over the control of approximately 88 and 80 percent for the 1972 and 1965 clearcuts, respectively.

Sulfate

Grand mean sulfate concentrations for the 1973 sampling period were 2.9 mg/1 from the control, 5.2 mg/1 from the 1972 clearcut, and 3.6 mg/1 from the 1965 clearcut (Table 48). The grand mean concentration from the 1972 clearcut was 79.3 percent greater than from the control while the 1965 clearcut was 24.1 percent greater than the control. Sulfate was determined only during 1973.

Table 47. Potassium collected (mg) by an average "deep" lysimeter* during 1973.

Sampling Dates	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06 + 15-73	.349	.202	.505
6-22 + 29-73	.533	.445	.457
7-06 + 13-73	.281	.635	.519
7-21 + 27-73	.340	.623	.634
8-03 + 09-73	.307	.638	.508
8-17 + 24-73	.113	.658	.624
10-03 + 10-73	.109	.613	.413
Grand Total	2.032	3.814	3.660

*Tube-tension lysimeters at depths from 75 to 100 cm.

The weekly mean concentration from the control decreased from 3.8 mg/l in early June to 1.1 mg/l in late June (Figure 31). From this season low the mean increased to a season high of 5.5 mg/l in mid- to late August and then decreased to 3.7 mg/l in early October.

The weekly mean concentration from the 1965 clearcut decreased from 4.2 mg/l in early June to 0.9 mg/l in late June. This was followed by a gradual rise to 5.2 mg/l in early August and a subsequent decrease to 3.4 mg/l in early October.

The pattern of weekly mean concentrations from the 1972 clearcut was similar to the other two treatments with the exception that the decrease in October did not occur. From the early June value of 6.2 mg/l, the mean concentration decreased to 2.0 mg/l in late June and then steadily increased to 10.0 mg/l in early October.

Concentration data from "shallow" and plate lysimeters is reported in Appendix D, Table 5.

Comparisons of grand mean treatment concentrations showed the 1972 clearcut to be significantly greater than the other two treatments at an alpha level of 0.005. Differences between the 1965 clearcut and the control were not statistically significant. Results of an analysis of variance are contained in Appendix E, Table 6.

Total milligrams of sulfate collected by average lysimeters during 1973 were 4.4, 15.3, and 8.8 from the control, 1972, and 1965 clearcuts, respectively (Table 49). Totals from the 1972 and 1965 clearcuts were approximately 240 and 100 percent greater, respectively, than from the control.

Table 48. Weekly and grand mean sulfate concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E. 1/	N 2/	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	3.8	.96	9	6.2	1.37	15	4.2	.65	14
6-22 + 29-73	1.1	.54	14	2.0	.88	14	.9	.30	16
7-06 + 13-73	1.8	.35	13	2.4	.56	14	3.2	.70	12
7-21 + 27-73	3.0	.75	13	3.4	.31	14	3.5	.53	13
8-03 + 09-73	2.7	.48	12	5.5	.69	14	5.2	.41	13
8-17 + 24-73	5.5	2.21	6	6.3	.55	16	5.0	.68	13
10-03 + 10-73	3.7	.70	9	10.0	1.43	16	3.4	.39	12
Grand mean	2.9	.32	76	5.2	0.41	103	3.6	.24	93

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 31. Weekly mean sulfate concentrations from "deep" lysimeters (75 - 100 cm) during 1973. Squares, circles, and asterisks represent the control, 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.

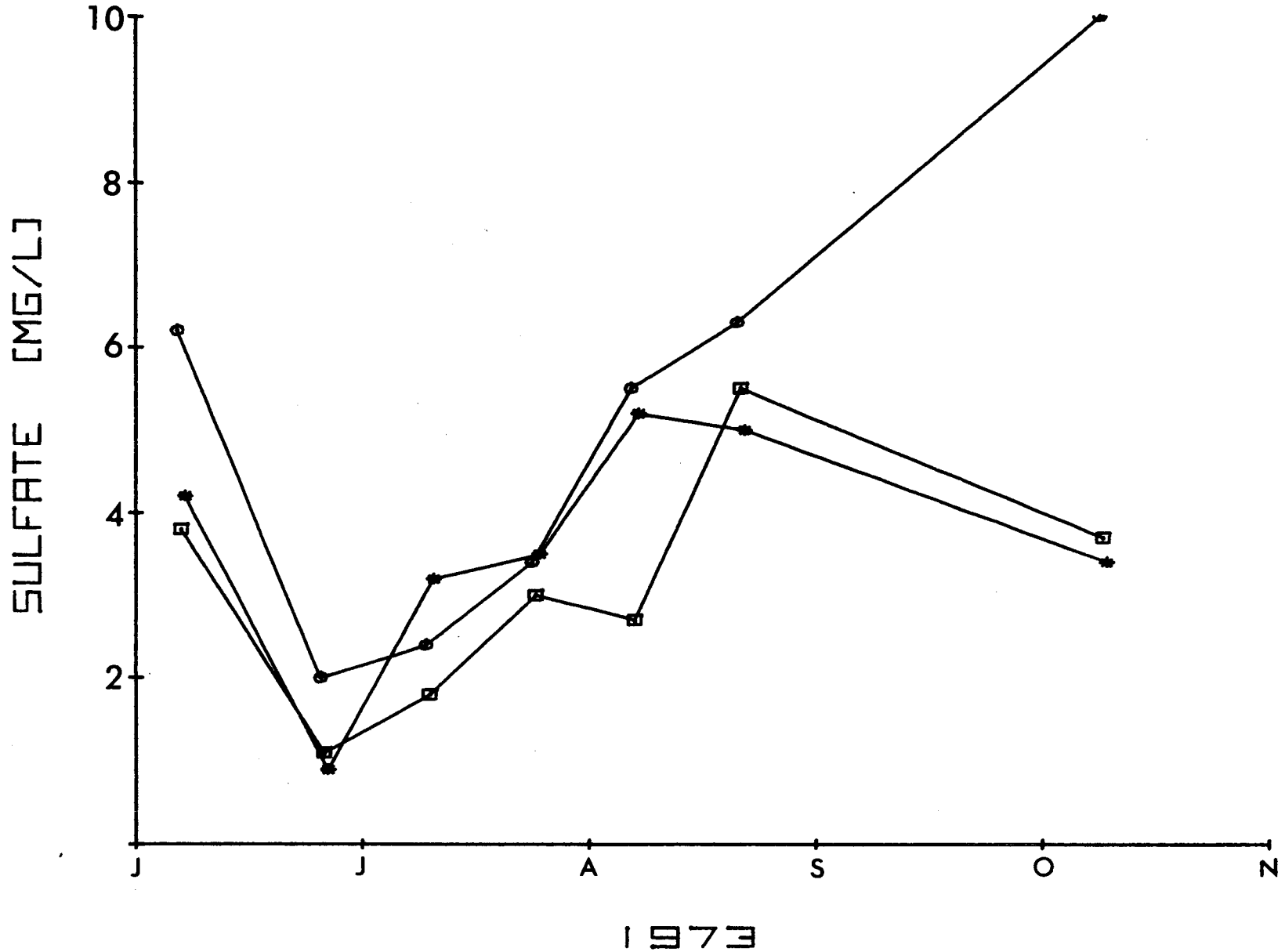

SULFATE [MG/L]
10
8
6
4
2
J
J
A
S
O
N
1973

Table 49. Sulfate collected (mg) by an average "deep" lysimeter* during 1973

Sampling Date	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06 + 15-73	1.326	3.099	1.179
6-22 + 29-73	.309	.636	.216
7-06 + 13-73	.362	.725	.923
7-21 + 27-73	.926	1.513	1.387
8-03 + 09-73	.692	2.338	1.885
8-17 + 24-73	.390	2.589	1.950
10-03 + 10-73	.446	4.381	1.277
Grand Total	4.451	15.281	8.817

*Tube-tension lysimeters at depths of 75 to 100 cm.

Chloride

Grand mean chloride concentrations were 4.1 mg/l from the control, 2.8 mg/l from the 1972 clearcut, and 2.5 mg/l from the 1965 clearcut for the period of sampling in 1973 (Table 50). Grand mean concentrations were 32 and 39 percent less from the 1972 and 1965 clearcuts, respectively, than from the control. Chloride was only determined in 1973.

The weekly mean chloride concentration from the control decreased from 5.8 mg/l in early June to 2.8 mg/l in late June (Figure 32). The mean concentration then gradually increased through July, then increased sharply in early August to 6.6 mg/l, and then decreased to 2.2 mg/l in early October, 1973.

The 1972 clearcut weekly mean concentration decreased from 3.5 mg/l in early June to 2.2 mg/l in late June and then held fairly constant at between 3.0 mg/l and 2.5 mg/l for the remainder of the year.

The weekly mean concentrations from the 1965 clearcut exhibited a pattern almost identical to the control but at lower concentrations. From an initial concentration of 3.7 mg/l, the mean decreased to 2.0 mg/l in late June, remained constant during July at about 2.2 mg/l, increased to 3.8 mg/l in early August, and then decreased to 1.2 mg/l in early October.

Mean concentration data from "shallow" and plate lysimeters is tabulated in Appendix D, Table 6.

Comparisons of grand mean concentrations showed the clearcut treatments to be significantly less than the control at an alpha level of 0.005. There was no statistically significant difference between grand mean concentrations from the two clearcuts. Results of an analysis of variance are contained in Appendix E, Table 7.

Table 50. Weekly and grand mean chloride concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	5.8	1.42	9	3.5	.87	15	3.7	.61	14
6-22 + 29-73	2.8	.76	14	2.2	.30	14	2.0	.19	16
7-06 + 13-73	3.3	.68	13	3.0	.46	14	2.1	.26	13
7-21 + 27-73	3.6	1.10	13	3.0	.34	14	2.3	.44	15
8-03 + 09-73	6.6	1.90	13	2.5	.33	14	3.8	.84	13
8-17 + 24-73	5.0	1.26	4	2.6	.32	16	2.1	.12	11
10-03 + 10-73	2.2	.18	9	2.8	.38	16	1.2	.17	12
Grand mean	4.1	.40	75	2.8	.17	103	2.5	.19	94

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 32. Weekly mean chloride concentrations from "deep" lysimeters (75 - 100 cm) during 1973. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.

CHLORIDE [MG/L]
7
5
3
1
J
J
A
S
O
N
1973

Table 51. Chloride collected (mg) by an average "deep" lysimeter* during 1973

Sampling Dates	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06 + 15-73	2.024	1.179	1.039
6-22 + 29-73	.786	.700	.481
7-06 + 13-73	.663	.907	.663
7-21 + 27-73	1.111	1.335	.911
8-03 + 09-73	1.691	1.063	1.378
8-17 + 24-73	.355	1.069	.819
10-03 + 10-73	.265	1.227	.451
Grand Total	6.895	7.480	5.742

*Tube-tension lysimeters at depths of 75 to 100 cm.

During 1973, 6.9, 7.5, and 5.7 milligrams of chloride were collected by average lysimeters from the control, 1972, and 1965 clearcuts, respectively (Table 51). The total amount collected from the 1972 clearcut was 8.5 percent greater, and from the 1965 clearcut was 16.7 percent less, than that collected from the control.

Sodium

Grand mean sodium concentrations were 2.3, 2.6, and 2.6 mg/l during 1973 and 1.4, 1.7, and 1.6 mg/l during the 1974 sampling period from the control, 1972 clearcut, and 1965 clearcut, respectively (Tables 52,53). Weekly mean concentrations were similar from the three treatments during both years. Concentration determinations were made to the nearest 0.1 milligram per liter during 1973 and to the nearest milligram during 1974.

In 1973, the control weekly mean concentration decreased from 2.9 mg/l in early June to 1.9 mg/l in early October with only minor fluctuations during the period (Figure 33). During 1974, the weekly mean concentrations from the control decreased from 1.8 mg/l in late May to approximately 1.3 mg/l during June.

The weekly mean concentration from the 1965 clearcut decreased sharply from 4.7 mg/l in early June, 1973, to 2.5 mg/l in late June and then continued a gradual decline to 1.7 mg/l in early October. Concentrations remained fairly constant at about 1.7 mg/l during the 1974 sampling period.

The weekly mean concentration from the 1972 clearcut decreased gradually during the 1973 period from 2.8 mg/l in early June to 1.7 mg/l in early October with only minor fluctuations during the period. The 1974 concentrations were similar in magnitude and direction to the 1965 clearcut for that year.

Table 52. Weekly and grand mean sodium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	2.9	.63	9	2.8	.51	15	4.7	.71	14
6-22 + 29-73	2.2	.43	14	2.2	.24	14	2.5	.23	16
7-06 + 13-73	2.4	.41	13	2.7	.17	14	2.6	.22	13
7-21 + 27-73	2.3	.40	13	2.3	.21	14	2.2	.16	14
8-03 + 09-73	2.2	.35	13	2.2	.19	14	2.5	.29	14
8-17 + 24-73	2.5	.38	10	1.9	.16	16	2.1	.23	13
10-3 + 10-73	1.9	.41	9	1.7	.24	16	1.7	.23	12
Grand mean	2.3	.16	81	2.2	.10	103	2.6	.16	96

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Table 53. Weekly and grand mean sodium concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1974.

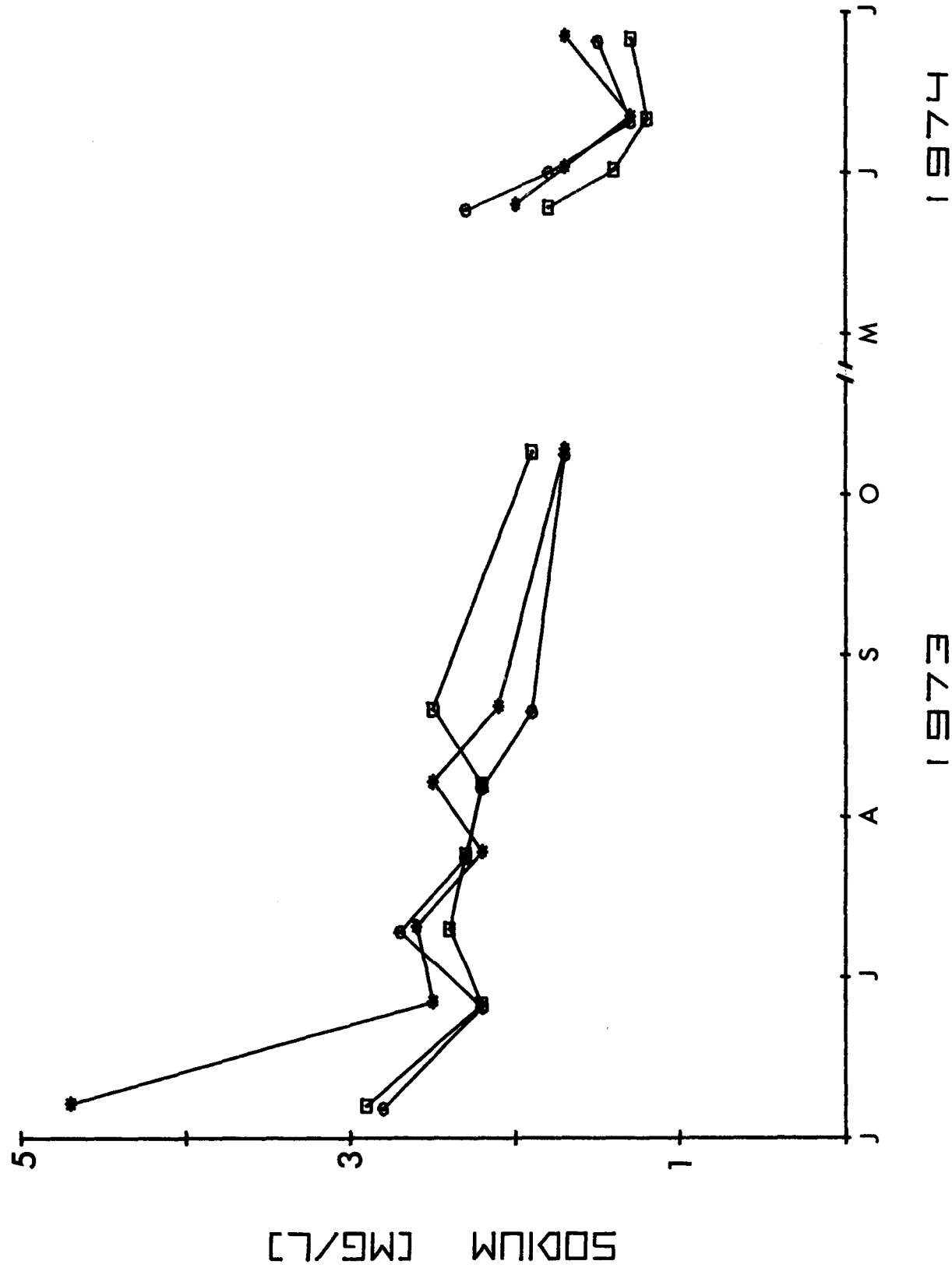
Sampling date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
5-27-74	1.8	.34	10	2.3	.40	14	2.0	.28	12
6-03-74	1.4	.20	11	1.8	.22	15	1.7	.16	14
6-12 + 17-74	1.2	.11	15	1.3	.12	16	1.3	.15	16
6-24 + 7-03-74	1.3	.15	15	1.5	.16	15	1.7	.16	15
Grand mean	1.4	.10	51	1.7	.13	60	1.6	.10	57

* Tube-tension lysimeters at depths of 75 to 100 cm.

1/ Standard error of the mean.

2/ Number of samples analyzed.

Figure 33. Weekly mean sodium concentrations from "deep" lysimeters (75 - 100 cm) during 1973 and 1974. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.


SODIUM (MG/L)
5
3
1
J
A
S
O
N
J
J
1973
1974

Concentration results from "shallow" and plate lysimeters are tabulated in Appendix D, Table 7.

Total milligrams of sodium collected during 1973 by average lysimeters were 3.79, 5.94, and 5.91 from the control, 1972, and 1965 clearcut, respectively (Table 54). About 56 percent more sodium was collected from the two clearcuts than from the control during 1973.

Comparisons between treatment grand means from 1973 revealed that only the 1965 clearcut and the control were significantly different at an alpha level of 0.250. The 1974 grand mean concentrations from the 1972 clearcut and 1965 clearcut were significantly greater than the control mean at alpha levels of 0.100 and 0.250, respectively. The two clearcuts were not statistically different during the 1974 period. Analysis of variance results are contained in Appendix E, Table 8.

Phosphate

The grand mean phosphate concentrations for 1973 were 0.012, 0.016, and 0.018 mg/l from the control, 1972 clearcut, and 1965 clearcut, respectively (Table 55). The 1972 clearcut grand mean was 33.3 percent greater than the control grand mean while the 1965 clearcut grand mean concentration was 50.0 percent greater than the control.

The weekly mean concentration from the control declined steadily during the season from 0.016 mg/l in early June, 1973, to 0.007 mg/l in mid-August (Figure 34).

Table 54. Sodium collected (mg) by an average "deep" lysimeter* during 1973.

Sampling Dates	Treatment		
	Control	1972 Clearcut	1965 Clearcut
6-06 + 15-73	1.012	.943	1.319
6-22 + 29-73	.617	.700	.601
7-06 + 13-73	.482	.816	.750
7-21 + 27-73	.710	1.024	.872
8-03 + 09-73	.564	.935	.906
8-17 + 24-73	.177	.781	.819
10-03 + 10-73	.229	.745	.639
Grand Total	3.791	5.944	5.906

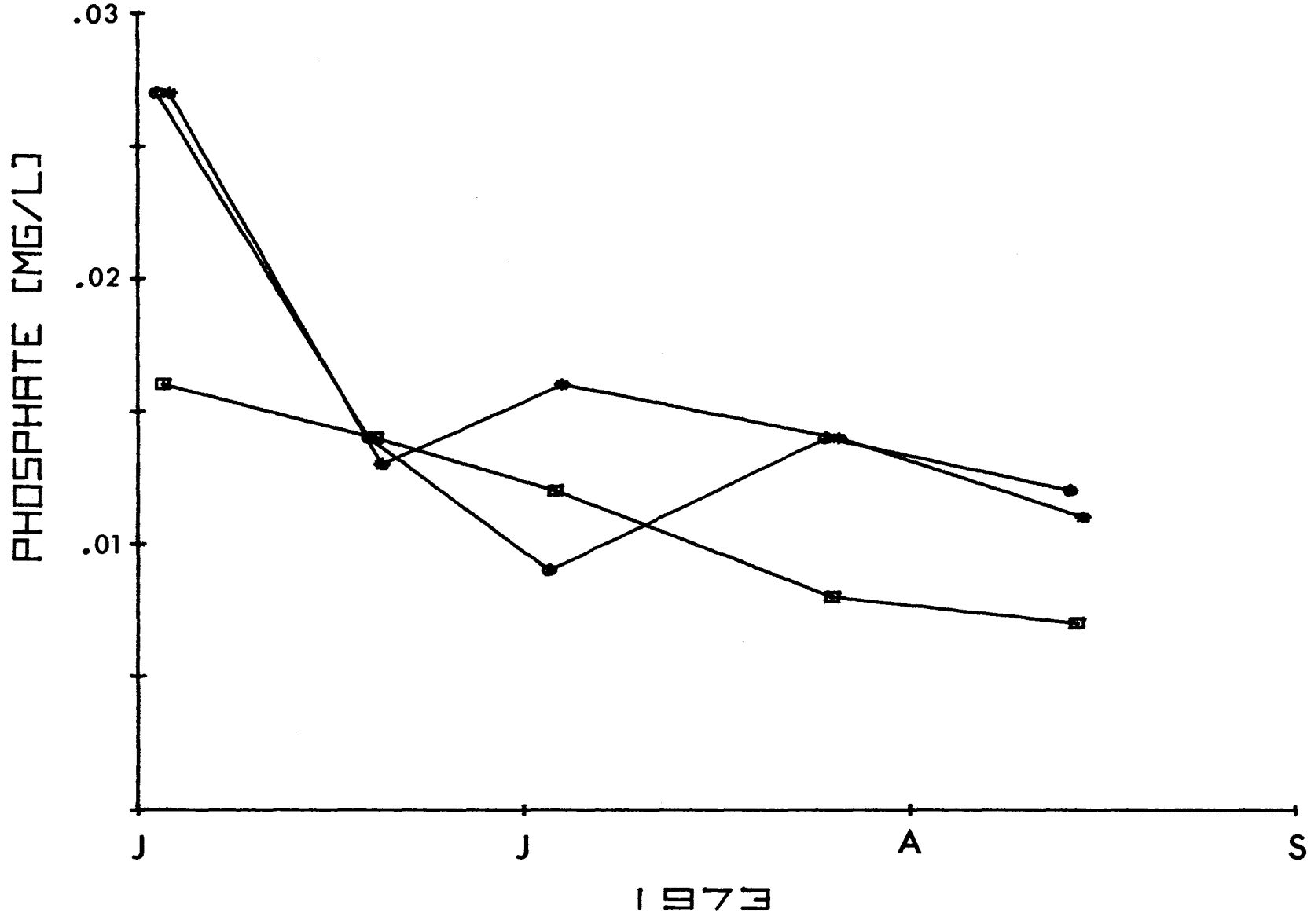
*Tube-tension lysimeters at depths of 75 to 100 cm.

Table 55. Weekly and grand mean phosphate concentrations (mg/l) in soil-water samples from "deep" lysimeters* during 1973.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06-73	.016	.006	6	.027	.004	13	.027	.004	12
6-22-73	.014	.002	9	.014	.002	10	.013	.002	10
7-06-73	.012	.001	7	.009	.002	10	.016	.003	8
7-27-73	.008	.003	4	.014	.004	8	.014	.005	6
8-17-73	.007	.006	3	.012	.005	7	.011	.005	6
Grand Mean	.012	.002	29	.016	.002	48	.018	.002	42

*Tube-tension lysimeters at depths of 75 to 100 cm.
1/ Standard error of the mean.
2/ Number of samples analysed.

Figure 34. Weekly mean phosphate concentrations from "deep" lysimeters (75 - 100 cm) during 1973. Squares, circles, and asterisks represent the control, the 1972 clearcut, and the 1965 clearcut, respectively. Means are located at the mid-point of a sampling period.


.03
.02
.01
PHOSPHATE [MG/L]
J
J
A
S
1973

The weekly mean concentration from the 1972 clearcut decreased from 0.027 mg/1 in early June to 0.009 mg/1 in early July, increased to 0.014 mg/1 in late July, and then decreased to 0.012 mg/1 in mid-August.

The weekly mean concentration from the 1965 clearcut decreased from 0.027 mg/1 in early June to 0.013 mg/1 in late June, then increased to 0.016 mg/1 in early July and from there steadily decreased to 0.011 mg/1 in mid-August.

Concentration data from "shallow" and plate lysimeters are reported in Appendix D, Table 8.

S-contrasts between grand mean concentrations resulted in the 1965 clearcut being significantly greater than the control at an alpha level of 0.250. The two other grand mean concentration contrasts were not statistically significant. Analysis of variance results are contained in Appendix E, Table 9.

Total milligrams of phosphate collected were not calculated because of the infrequency of the analyses.

Miscellaneous Determinations

Specific conductance and bicarbonate analyses are contained in Tables 56 and 57. In most cases, analyses were conducted at least three weeks from the date of sampling. Because of the time interval, these results are considered as rough approximations only.

Occasional pH measurements were made at the time samples were removed from the lysimeters. The pH values from "deep" lysimeters ranged from 5.6 to 6.6 while means from all treatments were approximately 6.0. These values are also difficult to interpret because the process of removing the water-sample from the lysimeter involves forcing air through the instrument which undoubtedly alters the pH of the sample.

Determinations of solutes from streams, precipitation, surface-runoff, and from a spring were made on several occasions during the two years (Table 58). The rain sample was taken at Ft. Collins, four hours after the commencement of a rain that lasted most of the day. Snow samples were collected within one week of a precipitation event. The spring is located about 1200 ft. to the east of the control treatment in a contiguous uncut area. The south fork of Panhandle Creek and Sign Creek drain a mosaic of cut and uncut areas. Several clearcuts are present in the upstream area of Killpecker Creek but samples were taken approximately one mile downstream from these areas. North Lone Pine Creek has no known clearcuts above the point of sampling, but it does drain a small meadow and is in an area of several small prospect sites.

Concentrations obtained from streams, surface runoff, and the spring are generally within the range of values obtained from the control from "deep" lysimeters. Snow and rain samples are generally less than mean concentrations from the control.

Table 56. Weekly and Grand mean* specific conductance (micromhos/cm) from "deep" lysimeters during 1973 and 1974.

Sampling Date	Treatment: Control Mean[1/]	Control S.E.[2/]	Control N	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06 + 15-73	64	10.0	9	81	12.8	15	76	5.6	14
6-22 + 29-73	47	9.0	14	45	3.9	14	52	4.1	16
7-06 + 13-73	44	5.4	13	60	5.2	13	60	4.9	12
7-21 + 27-73	46	3.7	13	58	4.9	14	58	3.2	14
8-03 + 09-73	52	6.1	13	69	4.8	14	70	4.8	14
8-17 + 24-73	74	14.1	10	75	3.6	16	83	11.4	14
10-03 + 10-73	50	6.4	9	96	8.8	16	58	5.4	12
Grand Mean-1973	53	3.1	81	70	3.1	102	65	2.5	96
5-27-74	47	5.7	10	90	16.2	14	69	14.1	12
6-03-74	34	6.1	11	67	7.5	15	45	4.2	14
6-12 + 17-74	30	2.5	15	56	5.9	16	38	4.8	16
6-24 + 7-03-74	31	1.9	15	57	3.5	15	35	2.2	14
7-09-74°	25	1.8	13	55	4.7	14	28	1.7	13
7-16-74°	40	2.3	12	79	4.6	14	40	2.1	12
7-23-74°	42	5.1	9	86	6.1	14	38	2.3	13
Grand mean-1974	35	1.5	85	70	3.2	102	41	2.4	94

* Tube-tension lysimeters at 75 to 100 cm.
1/ Standard error of the mean.
2/ Number of samples analysed.
° Samples analysed one day after sampling date. All other samples were analysed at least three weeks from date of sampling.

Table 57. Weekly and Grand mean bicarbonate concentrations (mg/l) from "deep" lysimeters* during 1973.

Sampling Date	Treatment								
	Control			1972 Clearcut			1965 Clearcut		
	Mean[1/]	S.E.[2/]	N	Mean	S.E.	N	Mean	S.E.	N
6-06-73°	12	1.3	6	22	1.7	12	29	8.1	12
7-21 + 27-73	18	2.0	13	16	1.4	14	12	2.4	15
8-03 + 09-73	13	1.4	13	12	1.0	14	13	1.7	13
8-17 + 24-73	8	0.2	3	14	1.7	16	11	2.8	12
10-03 + 10-73	10	1.5	9	9	0.7	16	8	0.8	12
Grand Mean	13	0.9	44	14	0.8	72	14	1.9	64

* Tube-tension lysimeters at depths of 75 to 100 cm.
1/ Standard error of the mean.
2/ Number of samples analysed.
° Samples analysed on 6-8-73. All other samples analysed at least three weeks from date of sampling.

Table 58. Mean concentrations (mg/l) of solutes determined from several water sources in the general vicinity of the clearcut treatments. Values in parenthesis are the number of samples analysed. Rain sample was taken at Ft. Collins, Colo.

Source	Solutes				
	NO_3^-	Ca^{++}	Mg^{++}	Na^+	K^+
Surface runoff	.32 (14)	1.6 (10)	1.1 (9)	1.7 (9)	1.1 (9)
Spring	.09 (5)	2.1 (4)	0.6 (4)	2.0 (5)	1.0 (4)
S. F. Panhandle Cr.	.05 (4)	3.1 (2)	0.9 (2)	2.2 (2)	0.4 (2)
Killpecker Cr.	.16 (4)	3.1 (2)	0.9 (2)	2.2 (2)	0.6 (2)
Sign Cr.	.30 (4)	3.1 (2)	1.0 (2)	2.2 (2)	0.4 (2)
N. Lone Pine Cr.	.03 (4)	3.4 (2)	1.1 (2)	2.9 (2)	0.4 (2)
Rain	.40 (1)	1.0 (1)	1.0 (1)	2.0 (1)	1.0 (1)
Snow	.33 (3)	1.0 (3)	1.0 (3)	2.5 (3)	1.0 (1)

Discussion

Water

Grand mean water losses from the three cutting treatments followed an expected order. The greatest loss of water occurred from the 1972 clearcut where almost all vegetation capable of causing significant transpirational loss was removed during the clearcutting operation. The average water loss from the control was the lowest for both years due to much greater transpiration and evaporation (interception). The average water loss from the 1965 clearcut was intermediate between the control and the 1972 clearcut. It is likely that transpiration from the 1965 clearcut was much less than from the control but greater than from the 1972 clearcut because some revegetation had occurred since the time of its cutting. Kochenderfer and Patric (1970) reporting on results from experimental clearcuts in West Virginia, noted that water yields from an uncut watershed were lowest, water yields from a clearcut watershed where trees less than five inches d.b.h. were left standing were intermediate, and water yields from a watershed that was clearcut and later herbicided to kill all remaining vegetation was greatest.

Gessel and Cole (1965) reported that before clearcutting of Douglas-fir, about 45 percent of precipitation moved through the top 36 inches of the forest soil, while after cutting, 74 percent of precipitation had reached this depth, an increase following cutting of 64%. In our study the grand mean volume from the 1972 clearcut was 77% greater than the control during the 1973 period. In an earlier study of a 30-year-old Douglas-fir stand, Cole, et al. (1961) noted that 70 percent of

precipitation was collected at a soil depth of 0.5 inches while at 28 inches only 35 percent of the water from precipitation remained.

Snow surveys on the three treatments during 1973 and 1974 showed total inches of water on the control plot to be approximately 50 percent greater than on the 1965 clearcut and 25 percent greater than on the 1972 clearcut. Snow on the 1965 clearcut was gone by the first of June in both years while snow still remained up until the second week of June on the 1972 clearcut and until the third week of June on the control plot. Snow accumulation appears to explain the higher mean weekly volumes observed from the control during the first few weeks of June, 1973.

The sharp increases in weekly mean volumes observed from all treatments in mid-July, 1973, are probably the result of the 3.12 inches of precipitation from July 12 to 22, 1973. A small storm (0.5 inches) on August 1, 1973, is probably the cause of the slight increase in mean volumes from the two clearcuts noted subsequent to this date.

Fredriksen (1972) in a study of a Douglas-fir forest in western Oregon, reported that water in the upper 30 cm of the forest soil reaches a minimum in late August or early September. Fredriksen's findings agree with the results obtained in this study where all three treatments exhibited seasonal low volumes from the August 7, 1973, sample. Results from the control are the most dramatic. No water was collected from the 16 "deep" lysimeters on this date.

The increases in mean volumes that occurred during September are apparently the result of precipitation events during that month and signal the beginning of the fall and winter soil-water recharge period.

Water volumes were not recorded during May and early June, 1974, but volumes obtained in late June relate well to volumes in late 1973, and suggest that volumes were higher in May and June.

Pierce, et al. (1970), Lynch, et al.(1972), Rothacher (1970a), and Hornbeck, et al. (1970) have all reported increased water volumes in streams following clearcutting and in most cases have noted significant increases during the normally low flow periods of the summer growing season. An increase in stream base flows during the summer could benefit stream fishes by providing more available living space and result in increased population sizes (Chapman, 1962). Increased summer base flows would also provide more area for plant and invertebrate communities. This would probably result in increased growth rates of higher trophic levels and so benefit the existing fishery in these streams. Because of revegetation of clearcut areas, these benefits would gradually diminish with time, but judging from volumes obtained from the 1965 clearcut, beneficial effects would still be present nine years after cutting.

The possibility also exists that clearcutting may effect peak stream flows and cause damage in excess of what would have occurred naturally. Flooding at certain times of the year can cause high mortality of incubating fish eggs, destroy newly-hatched fry, and cause channel scouring and bank erosion which could seriously reduce standing crops of aquatic plants and invertebrates (Chapman, 1962).

It is generally agreed (Hornbeck, et al., 1970; Kochenderfer and Patric, 1970; Rothacher, 1970), however, that under recommended clear-cutting techniques (minimal soil compaction and mineral soil exposure)

the intensity of major spring floods will not be increased. There are two main reasons for this conclusion. First, soil water capacities are usually at a maximum in early spring due to winter recharge and so clear-cutting generally has little effect on floods at this time of year (Rothacher, 1970b). Second, clearcutting "smooths out" the stream hydrograph. As mentioned earlier, snow accumulation was greater and remained longer on the control. Desynchronization of snow melt from cut and uncut areas might result in a reduction of peak flows (Goodell, 1959; Rothacher, 1970).

Peak flows during the summer might be increased, however, because water storage in excess of that from undisturbed watersheds occurs on clearcut sites due to lower transpirational and evaporational losses. High intensity summer storms on clearcut watersheds could then result in some flooding because of higher soil moisture conditions in these areas (Kochenderfer and Patric, 1970).

Nitrogen

Nitrogen losses from undisturbed forest sites are generally very small relative to other nutrients. The small grand mean concentrations from the control for both years is similar to values reported from other forested watersheds.

Cole, et al. (1961) reported an average nitrogen concentration of 0.37 mg/l from January to July in soil-water samples at a depth of 28 inches from a 30-year-old Douglas-fir system in Washington. In another study of a Douglas-fir system, Cole, et al.(1967) reported an annual loss of nitrogen of 0.6 kg/ha. Fredriksen (1972) determined that the nitrogen losses for two consecutive years averaged about 0.5 kg/ha from

a Douglas-fir forest. Gessel and Cole (1965) reported an annual loss at a depth of 36 inches, again from a Douglas-fir system, of about 0.63 kg/ha. Stottlemyer (1968) in a study of a lodgepole pine system in Colorado, concluded that although nitrates were not determined, low cation concentrations in streams draining uncut watersheds precluded large amounts of nitrates in stream effluents.

Losses of nitrates from undisturbed eastern deciduous forests appear to be greater than from western coniferous systems. An oak-hickory and yellow pine forest in West Virginia exhibited an annual nitrate loss of 3.0 kg/ha. (U.S. Forest Service, 1971a). At Hubbard Brook in New Hampshire, the annual losses of nitrates from a control watershed were 1.3 and 2.8 kg/ha for two consecutive years. Verry (1972) reported average nitrate concentrations of 0.30 to 0.12 mg/1 in streams draining an aspen, birch, and black spruce watershed in Northern Minnesota.

Nitrogen losses following clearcutting of lodgepole pine were much greater than from an uncut area during this study. The increases in nitrate concentrations from the two clearcuts accounted for the major portion of the total nitrogen loss.

More drastic losses of nitrogen were reported from the Hubbard Brook experiment where all trees were cut and left lying and herbicide was applied to the watershed to prevent any vegetation regrowth (Likens, et al., 1969, 1970; Borman, et al., 1968; Pierce, et al.,1970, 1972). Average nitrate concentrations in stream water increased from 0.69 to 38.4 mg/1 during the first year following clearcutting. By the second year following cutting the average concentration had reached 52.9 mg/1.

In a study following a conventional clearcutting operation at Hubbard Brook, Pierce, et al. (1972) reported nitrate concentrations were only about one-third as great as those from the herbicided watershed. At the Fernow Experimental Forest in W. Virginia, nitrate losses increased from about 3.0 kg/ha to 36.0 kg/ha for the first year following clearcutting (U.S. Forest Service, 1971a).

Differences between the forest control and the 1972 clearcut were not great until mid-August, 1973, and by 1974 the nitrate concentrations from the 1972 clearcut even exceeded those from the 1965 clearcut. For the 1974 period the 1972 clearcut lost 15 times more nitrate than the control and almost twice as much as the 1965 clearcut.

Many studies reporting only small increased nutrient losses following clearcutting have reported data for only the first year after cutting. It may be as Verry (1972) suggests, that one year is simply not enough time for a significant amount of decomposition to occur in many climates. In this regard, it was noted that the needles remaining after our clearcutting were still green the following August.

Studies conducted in cooperation with the IBP Coniferous Biome Program have shown that the total litter fall for a one year period from July 1973 to June 1974 on the control site was 1211 kg/ha (Unpublished data). Considering that the biomass of the O_1 horizon on the control site in 1973 was 15,625 kg/ha(Table 11), this would indicate that the O_1 horizon represents 12.9 years accumulation of litter. This further emphasizes the relatively long period of time required before complete decomposition of litter takes place.

In Fredriksen's study (1970), mean annual nitrate concentrations doubled the first year following clearcutting, increased by five times after slash burning the second year, and by the third year after cutting (second year after slash burning) the mean nitrate concentration had increased by 20 times that of the first year control value. In New Hampshire, nitrate losses from a cut watershed for the second year following cutting were double the losses observed the first year (Pierce, et al., 1970).

Concentrations obtained in late October, 1972, are in agreement with those obtained the following year. The October, 1972.concentrations from the 1972 clearcut are lower than those the following spring but are similar to control concentrations. The 1972 concentrations were taken immediately after clearcutting and should reflect control values. The 1972 concentrations from the 1965 clearcut are probably representative considering the late fall samples in 1973 and allowing for a decreasing trend evident during that period.

Ammonium concentrations from the two clearcuts averaged only one-half that from the control treatment during 1973. Of the total inorganic nitrogen (ammonium plus nitrate) lost during 1973, ammonium accounted for 40 percent of the loss from the control while ammonium losses from the 1972 and 1965 clearcuts accounted for only 18 and 3 percent, respectively. Likens, et al. (1970) also noted a decrease in ammonium concentrations in each of two years following clearcutting. Fredriksen (1970) reported a large increase in ammonia following slash burning and a sharp decrease in concentration the second year after burning.

The most apparent explanation for the increase in nitrate concentrations and reduced ammonium concentrations is an increase in the nitrification process (Likens, et al., 1970, 1969; Pierce, et al., 1972). If loss of

nutrients was related solely to increased water movement, then the nitrate losses would have been considerably less from the clearcuts during our study and ammonium losses much greater. At Hubbard Brook, soil bacteria of the genera Nitrosomonas and Nitrobacter increased 18- and 34-times, respectively, following clearcutting (Likens, et al.,1969; Smith, et al., 1968).

Whether a significant amount of nitrification occurs in a climax forest is still unanswered (Likens, et al.,1969). It may be that nitrification is suppressed in a climax forest and that ammonium is the primary nitrogen compound utilized by growing vegetation. It has been pointed out that in soils with low pH, e.g., most coniferous forests soils, that nitrification proceeds slowly even in the presence of an adequate substrate, and nitrifying bacteria may even be absent (Alexander, 1961; Jackson 1967; Remezov and Pogrebryak, 1969; Gigon and Rorison, 1972). It is obvious that some nitrification occurs in lodgepole pine forests since measurable concentrations were detected.

Further evidence supporting a change in nitrogen metabolism after clearcutting is presented by Rice and Pancholy (1973). Reporting on results from several vegetation types in various stages of succession, the authors demonstrated that as succession proceeds toward a climax system, nitrogen metabolism shifts from a nitrate base to an ammonium base. They also observed a decrease in the number of nitrifying bacteria as succession proceeded. They attributed these changes to inhibition of nitrifying bacteria by tannins and tannin derivates which accumulate as a climax system is approached. A few measurements during our study in July and August, 1974, suggest that tannins from "deep" lysimeters were 40 to 50 percent greater from the control and 1972 clearcut than from the 1965 clearcut (Unpublished data).

The significance of these results is that both nitrogen and energy would be conserved in a climax community if ammonium were the principal nitrogen source available to plants (Rice and Pancholy, 1973). Because ammonium is a cation, it is subject to adsorption on cation exchange complexes in the soil and as such is less subject to leaching. Nitrate, in contrast, is a highly soluble anion and is subject to rapid leaching from the system. Energy would be conserved because a reduction step would not be required before ammonium could be incorporated into organic compounds, i. e., as an amine group.

An increase in nitrification appears to be the most logical explanation for the nitrogen losses from the three treatments. Ammonium losses were high from the control relative to the clearcuts while the nitrate losses show a reciprocal relation. Nitrate losses were not significantly greater from the 1972 clearcut until almost one-year after clearcutting, probably the time required for the nitrifying bacteria to increase to the levels necessary to produce significant amounts of nitrate. Any ammonium produced during this time could have been adsorbed on exchange sites and would not have appeared in soil-water samples below the rooting zone.

Not only was the total amount of nitrate increased by clearcutting at Hubbard Brook, but the seasonal concentration pattern was reversed (Likens, et al., 1970; Johnson, et al.,1969). Nitrate concentrations from the uncut watershed exhibited seasonal lows during the summer with concentrations increasing during November and reaching seasonal highs in the spring. After cutting, the highest concentrations were observed in late summer and fall and lows occurred in the spring. Similar patterns were observed in our study during the 1973 sampling period. The decrease in nitrate concentration

in late July, 1973, can be accounted for by the rain storms prior to this time. These rains apparently increased the concentration at 75 to 100 cm by flushing accumulated nitrates from the upper soil layers. After this flushing, concentrations returned to levels present before the rains and then continued to build up to fall highs. During the period in 1974, the 1972 clearcut exhibited a pattern similar to that from the 1965 clearcut in the previous year while the 1965 clearcut concentrations were lower than from the year before. Nitrate concentrations from the clearcuts are even more striking when the small variation in weekly concentrations from the control are considered.

Comparison of nutrient composition of logging residues in 1973 and live trees (Appendix C, Table 4) reveals lower nitrogen in twigs, stems, and branches from the 1965 clearcut while the slash from the 1972 clearcut and live trees showed little difference. Leaching and decomposition apparently reduced the total nitrogen contents from logging slash which increased the nitrogen source for nitrifying bacteria. The percent total nitrogen in the 01 and 02 soil layers also supports the theory of increased nitrification. The 01 horizon from the 1965 clearcut had the lowest percent total nitrogen of the three treatments in 1971 and 1972 (Appendix B, Table 3). The 02 horizon from the 1965 clearcut had the lowest nitrogen percent for all three years measured. The quantity of total nitrogen (kg/ha) in the forest floor was also lower for the 1965 clearcut.

Nitrate-nitrogen composition of the soils during 1971 revealed that concentrations present in the control organic horizons were greater than from the 1965 clearcut. Nitrates were not detectable in A2 and B2 horizons which supports the assumption that nitrates present in water below the rooting zone are lost to ground water supplies. For the control, the soil-

nitrate data are not in conflict with soil-water data since nitrate concentrations in soil-water samples at 10 cm were at times greater than those from the clearcuts (Table 34). Because of less soil-water movement from the control, nitrates that are produced probably accumulate to a greater extent than those from the clearcuts where leaching is more prevalent.

Occasional analyses of streams in the same general area as the three treatments failed to reveal nitrate concentrations similar to those in soil-water samples from the treatments, although in some cases probably over 50 percent of their water originated from clearcut areas. Concentrations in streams more nearly reflected concentrations from the control. It can be argued that stream concentrations, in most cases, are not representative of input concentrations. Normal nitrate concentrations in streams are usually low because of rapid uptake by aquatic plants (Hynes, 1972). Brehmer, et al. (1969) reported that in a Michigan stream accrued nutrients were removed from solution within 0.6 miles downstream from a sewage outfall. Adams, et al. (1971) and Gossett and Norris (1971) have also noticed this occurrence and have attempted to use nutrient contents of plants as an indicator of past water concentrations. Brehmer, et al. (1969) also reported that biological response (and thus removal) to introduced nutrients was greatest during periods of high production, i. e., during the summer and fall. Nutrients entering streams draining clearcut watersheds could be rapidly removed from solution resulting in lower concentrations. Nutrient losses based on stream concentrations would then underestimate actual nutrient losses. These plants could become

detached at some later date and flush downstream without ever being detected by standard water sampling techniques.

Streams are heavily dependent upon allochthonous material to provide an energy base to support their heterotrophic communities (Nelson and Scott, 1962; Darnell, 1965; Warren, et al., Waters, 1969; Vannote, 1969; Hynes, 1972). In many streams, nitrogen may be in inadequate supply to provide for maximum growth of algae (Hynes, 1972; Martin and Goff). If such is the case in streams draining lodgepole pine forests, then the addition of nitrogen in the form of nitrates should result in increased primary production. This increase would eventually be reflected in the herbivore community and eventually in increased production of tertiary consumers. Pierce, et al. (1972) noted growths of algae *(Ulothrix zonata)* in streams following clearcutting. This species was not evident in streams draining uncut watersheds. Warren, et al. (1964) artificially enriched sections of Berry Creek in Oregon with one to four mg/l of sucrose and subsequently caused large increases in the bacterium *Sphaerotilus natans* chironomid larvae, and ultimately trout production. McConnell (1968) estimated that the organic compounds in oak litter extracts that entered a small southwestern inpoundment could account for a 16 percent increase in fish production.

Hynes (1969) states that the effects of enrichment in streams are not long-lasting once the addition of the nutrients are eliminated. Lakes, however, act as nutrient traps and can remain eutrophic for long periods of time. The effects of enrichment applies equally for lakes and streams. Lakes, however, are more complicated because of seasonal cycling of nutrients due to thermal stratification. During summer

thermal stratification,nitrogen may be depleted from the epilimnion while hypolimnetic waters may exhibit high ammonia concentrations resulting from reducing conditions present below the thermocline. Upon mixing (overturn) ammonia becomes distributed through the entire water column and is rapidly oxidized to ammonium and nitrate (Seruya and Berman, 1970). Some nitrogen is lost to bottom sediments (Edmondson, 1970; Sawyer, 1947) but a continual input of nitrogen in inflow water could result in serious eutrophication.

It is difficult to predict whether concentrations of nitrates have reached a peak from the 1972 clearcut or whether they will increase even more. At their present level they will probably result in some increased plant production in streams but excessive plant growth will probably not occur. Just how long the increased nitrate concentration will persist can not be determined, but the 1965 clearcut still exhibits significantly higher values nine years after clearcutting. Pierce, et al. (1972) indicated that peak nitrate losses probably occur during the second year in New Hampshire and that after four years the losses begin to decrease following utilization of readily available nitrogen sources. In lodgepole pine forests in Colorado the peak probably occurs later and the significant nitrate losses probably occur longer than in the Northwest because of slower decomposition rates.

Calcium

Calcium is among the most geographically variable of the common solutes found in natural waters. Concentrations of calcium are highly dependent upon the types of geologic formations through which the water

passes, and since there are so many types of rock containing calcium (Hem, 1970), it is difficult to compare losses of this element reported from different forest systems.

The weekly mean concentrations from the three treatments during both sampling years are within the range of concentrations reported by Stottlemyer (1968) for four streams in the Fraser, Colorado, area. Two of these streams exhibited ranges of 4.8 to 9.4 mg/1, while the other two ranged from 1.7 to 2.6 mg/1. Stottlemyer suggests that the higher values may be because these streams drain thin limestone deposits.

Cole, et al. (1961) reported average soil-water concentrations of 1.82 mg/1 at a soil depth of 28 inches from an infertile Douglas-fir site for a period from January to June. In other studies, Cole, et al. (1967) and Grier and Cole (1972) reported annual losses below the rooting zone of Douglas-fir stands were about 4.5 kg/ha, while Fredriksen (1972) reported calcium losses from an old-growth Douglas-fir system were 46 to 50 kg/ha for two consecutive years. Average annual stream concentrations reported from the latter study were about 5.0 mg/1. In another study by Fredriksen (1970), annual calcium losses of 2.5 kg/ha were reported from a Douglas-fir site. Average annual stream concentrations during this study were about 3.9 mg/1.

Calcium output of 6.9 kg/ha/yr was reported by Johnson and Swank (1973) from a mature hardwood forest at Coweeta, N. C., while at the Fernow Experimental Forest in W. Virginia, losses of about 18.4 kg/ha were reported from an uncut hardwood forest (U.S. Forest Service,1971a). Elwood and Henderson (1973) determined that a total of 117 kg/ha was removed annually in streams draining a Tennessee watershed underlain with dolomite deposits. Best and Monk (1974) in a study of two watersheds from Coweeta,

reported average calcium concentrations in the soil-solution at a depth of 25 cm of 1.1 mg/l from a hardwood forest and 1.7 mg/l from a white pine forest.

At Hubbard Brook and other areas in New Hampshire, average stream concentrations from uncut watersheds were approximately 1.5 mg/l (Likens, et al., 1970; Pierce, et al., 1972), while the annual output of calcium from the Hubbard Brook control watershed was about 11 kg/ha (Likens, et al., 1970).

Fredriksen (1970) determined that following clearcutting and burning of a Douglas-fir site, calcium concentrations increased 1.5 to 2 times while total losses were more than doubled those from a control watershed. Fredriksen's results are in close agreement with the results obtained during this study, both for concentrations and total losses. Gessel and Cole (1965) also noted a two-fold increase in calcium lost below a depth of 36 inches following clearcutting of Douglas-fir, however, average concentrations remained about the same as those from an uncut site. Likens, et al. (1970) reported a concentration increase of four to five times after clearcutting and herbicide treatment, while Pierce, et al. (1972) noted about a two-fold increase in average stream concentrations following conventional clearcutting operations in the same general area. Data from Pierce, et al. (1972) were for a period from April to November.

The pattern of weekly mean calcium concentrations and losses from the two clearcut treatments during 1973 i.e., low in the spring and increasing throughout the summer to a maximum in the fall, is similar to that reported for some other forest systems (Likens, et al., 1970; Johnson and Swank, 1973). Johnson and Swank (1973) reported that at Coweeta, where precipitation is rather uniform throughout the year, losses were lowest during the winter

months when biological activity was low and highest during the spring and summer months when biological activity was high and streamflow was relatively high. Likens, et al. (1970) reported that calcium concentrations followed nitrate concentrations and increased through the summer to peak in the fall.

Fredriksen (1972) reported that outputs of calcium from an uncut Douglas-fir system were highest in the winter months and lowest during the summer, just the reverse of concentration. This is similar to results obtained from the control during this study.

Soils data indicate that calcium is being leached from the surface horizons of the 1965 clearcut and is being deposited in the A2 and B2 horizons. It also appears upon examination of the composition of slash and live trees that a large part of the calcium comes from decomposition of slash and litter. There appears to be a net loss of calcium from most undisturbed forest systems (Likens, et al,1970; Fredriksen, 1972; Best and Monk, 1974; Johnson and Swank, 1973). It is possible that the initial concentration increase of calcium from the 1972 clearcut originated from the 01 horizon and that subsequent losses are due in large part to losses from slash. Since the concentration patterns from the three treatments are similar, leaching mechanisms are also probably the same but proceed at greater rates as a result of clearcutting. Likens, et al. (1969, 1970) have demonstrated that at Hubbard Brook the increased nitrification, and its resultant increase in nitrate anions and hydrogen cations, is the principal factor regulating losses of cations. McColl and Cole (1968) reported experimental results that support the hypothesis that bicarbonate and carbonate are the principal regulating anions. In either case, increased leaching would occur during period of increased temperature and ample

water movement (Grier and Cole, 1972). The bicarbonate theory is more applicable to the results obtained from the control treatment while both increased nitrification and bicarbonates are probable causes of increased cation losses from the two clearcuts.

The increased loss of calcium would probably not have any significant effects on stream biota since calcium is not considered a macronutrient for many algae (Smith, 1950). There could, however, be changes in the species of algae if sufficient amounts of calcium were added to streams over a period of time (Smith, 1950). More important to aquatic plants, however, are the associated carbonates of calcium which could supply additional amounts of carbon dioxide for photosynthesis (Reid, 1961; Smith, 1950).

Magnesium

Because grand mean magnesium concentrations for the 1973 period were about the same from the three treatments, most of the magnesium lost during this time was accounted for by increased water volumes from the two clearcuts. Other investigators have also reported only small increases in magnesium following clearcutting. Fredriksen (1970) reported average stream concentrations increased from 0.7 to 1.2 mg/l the first year following clearcutting of a Douglas-fir watershed while the annual loss increased almost three times. Pierce, et al. (1972) reported magnesium concentrations increased slowly after a December clearcutting from 0.4 mg/l to 0.8 mg/l the following August.

Annual losses of magnesium reported in the literature are variable and probably reflect differences in geologic origins of the soils. Annual losses from Douglas-fir systems ranged from about 12 kg/ha

(Grier and Cole, 1972; Fredriksen, 1972) to about 6 kg/ha (Fredriksen, 1970) while annual losses from eastern deciduous systems were about 3 kg/ha (Likens, et al., 1970; Johnson and Swank, 1973; Best and Monk, 1974).

Stottlemyer (1968) reported on streams in the Fraser, Colorado, area. He found two streams ranged in concentration from 0.8 to 1.3 mg/l while two others that might drain thin limestone deposits ranged from 1.9 to 3.4 mg/l. The lower range is consistent with the results from the three treatments in our study.

Comparisons between magnesium concentration from 1973 and 1974 may not be valid because of the reduced precision of the reported values during 1974. Grand mean concentrations from the two clearcuts, however, appeared to be greater than for the 1973 period in view of the relative decrease in the control grand mean.

Soils data during 1971 suggest that magnesium is higher in all horizons of the 1965 clearcut. It is possible that magnesium is adsorbed relatively more in these soils than other cations and so potential losses in soil-water are reduced.

Potassium

Hem (1970) states that potassium concentrations of more than a few tens of milligrams per liter are unusual except in water with very high dissolved solids concentrations. Our study and others support this statement. Likens, et al. (1967, 1970) reported an average concentration of approximately 0.2 mg/l from a control stream at Hubbard Brook, while Pierce, et al. (1972) presented data from another uncut watershed in the same area where the average stream concentration was 0.1 mg/l. Johnson

and Swank (1973) reported average stream concentrations of about 0.5 mg/1 from a mature hardwood watershed. Potassium concentrations in streams draining coniferous watersheds ranged from 0.37 to 0.95 mg/1 (Stottlemyer, 1968) and from 0.4 to 0.2 mg/1 (Fredriksen, 1970). Concentrations reported from the present study are similar to Stottlemyer's results for the streams at Fraser, Colorado.

Best and Monk (1974) reported concentrations of potassium of 1.2 mg/1 from a hardwood site and 1.9 mg/1 from a white pine forest in soil-water at a depth of 25 cm. Cole, et al. (1961) reported an average soil-water concentration of 0.28 mg/1 for a January to July period at a depth of 28 inches from an infertile Douglas-fir site in Washington.

The greater losses of potassium from the two clearcuts during both sampling years is mainly the result of increased water movement from the clearcut sites. Similar results have been reported from other coniferous systems following clearcutting. Gessel and Cole (1965) reported that the potassium output at a soil depth of 36 inches from a clearcut Douglas-fir site increased only ten percent the first year following clearcutting and concentrations were lower from the clearcut site. Fredriksen (1970) noted stream concentrations were about the same for the first year following clearcutting of Douglas-fir although the total loss of potassium was 1.6 times greater than the control. Following slash burning (one year after clearcutting) potassium concentrations remained constant at post-cutting levels while the control stream concentrations decreased 25 and 50 percent during the two year period. Actual losses after burning were 1.9 times greater than for the control watershed.

Stream concentrations of potassium increased an average of 12.5 times following clearcutting and herbicide applications at Hubbard Brook while annual losses were about 20 times greater than from the control watershed (Likens, et al, 1970). Pierce, et al. (1972) reported that stream concentrations increased from 0.1 mg/l before a December clearcutting to about 1.2 mg/l the following August.

Comparisons between results from 1973 and 1974 may not be valid because of the lower precision of the reported results during 1974. It does appear, however, that the average concentrations from the 1972 clearcut were relatively greater during the 1974 period in view of the concentration decrease experienced by the control in 1974.

The similar concentration patterns observed from all three treatments during 1973 are consistent with that reported by Likens, et al. (1970). They also noted a gradual decrease in potassium concentrations during the summer growing season.

The chemical composition of soil horizons, logging residues, and live trees suggest an explanation for the observed differences of potassium in the soil-water from the three treatments. The organic horizons of the 1965 clearcut had lower potassium contents that the other two sites. Slash from the 1965 clearcut also had lower potassium levels than either live trees or slash from the 1972 clearcut. The potassium content of the slash from the 1972 clearcut was similar to that from live trees except for needles which had about 38 percent less potassium than those from live trees. It is probable that the initial increase in potassium observed from the 1972 clearcut during 1973 is due to leaching of litter and slash deposited during cutting while losses in later years are probably the result of decomposition and leaching of the organic horizons. Gosy, et al.(1973)

reported rapid leaching losses of potassium from deciduous tree leaves. After six months, they found that potassium contents of leaves averaged only 25 percent of their original content. The rapid concentration increase observed in early June from the control and the 1972 clearcut may be due to leaching of litter (and slash) deposited during the fall and winter.

Concentrations of potassium reported for streams in other coniferous systems are generally less than soil-water concentrations obtained from the three treatments. This could be the result of potassium fixation by clay particles (Devlin, 1966) after passing below the rooting zone or in stream sediments. Herbaceous vegetation and tree reproduction from the 1965 clearcut contain significantly greater amounts of potassium than from the other two treatments. It is likely that aquatic plants would also decrease stream concentrations by uptake of additional potassium.

Sulfate

Comparisons of sulfate data from this study to similar studies reported in the literature is difficult because this anion is usually not included in routine water quality determinations. The Hubbard Brook experiments provide the only readily available source for comparison (Likens, et al.,1969, 1970; Pierce, et al., 1970, 1972). Sulfate concentrations at Hubbard Brook ranged from four to seven mg/l which is similar to the ranges obtained from the treatments during the present study.

The pattern of weekly mean concentrations from the three treatments does not follow a consistent concentration-volume relationship. One explanation for the pattern is that concentrations are related to periods of biological activity. The decrease in early June occurs at about the

time of maximum water movement and low biological activity and is probably the result of a decrease of the existing sulfate reserves in the soil by large volumes of water. The increasing concentrations observed during the summer occur at a time of increasing biological activity. Because there is more water available for leaching from the clearcuts during this summer period, more sulfate must be produced from them to off-set the dilution effect. The decrease in concentrations in October can again be accounted for by increased water movement and decreasing biological activity. The continued increased in concentration from the 1972 clearcut may be the result of some lag effect resulting from more favorable conditions on the site.

The significant increase in grand mean concentrations from the 1972 clearcut is in conflict with results obtained at Hubbard Brook where (Likens, et al.(1969,1970) reported that sulfate concentrations decreased following clearcutting. They attributed this mainly to possible toxic effects of nitrates on sulfur-oxidizing bacteria, such as *Thiobacillis thiooxidans*. However, application of a herbicide to the cutover watershed coincided with the decreased sulfate concentrations so that its effects on soil-bacteria may also be suspect. Pierce, et al. (1972) reported that sulfate concentrations did not decrease markedly during the first year after a commercial clearcutting operation in New Hampshire, however, nitrate concentrations were only one-third those observed by Likens, et al. (1970).

If an increase in nitrate production from a clearcut watershed can reduce populations of sulfur-oxidizing bacteria, then nitrate concentrations in excess of those observed by Pierce, et al. (1972), i. e.,23 mg/1, are

probably required. These levels were not detected from the treatments during the 1973 period.

It appears that in addition to nitrates, and probably bicarbonates, sulfates probably play a significant role in cation mobilization from the treatments and probably account for a major share of the cation losses from the control.

Chloride

Chloride and ammonium were the only two solutes measured during the present study that decreased in concentration following clearcutting. Although chloride concentrations were lower by about 35 percent from the two clearcuts compared to the control, the total milligrams collected from the three treatments were about the same for the 1973 sampling period.

The grand mean chloride concentration from the control for this study was about eight times greater than from control streams at Hubbard Brook (Likens, et al., 1970; Pierce, et al., 1970). For the first year following clearcutting and herbicide application, the Hubbard Brook control stream doubled in average concentration (Likens, et al.,1970). By the end of the second year following cutting, however, the stream concentration had returned to pretreatment levels. Pierce, et al., (1972) reported similar first year results from another clearcut in New Hampshire.

Likens, et al.,(1970) reported that the chloride budgets for undisturbed watersheds in the Hubbard Brook area appear to be balanced, i.e., inputs in precipitation equal outputs in streamflow.

Assuming budgets for chloride are balanced in lodgepole pine systems as they were for deciduous systems at Hubbard Brook, then an explanation can be advanced for the similarities in total losses from the three treatment sites despite the differences in grand mean concentrations. Assuming inputs of chloride are similar on all treatments and that it is rapidly leached below the rooting zone, then greater water utilization by vegetation on the control would result in increased concentrations from that site while concentrations from the clearcuts would be less because of greater water movement, i. e., an inverse concentration-volume relationship.

Sodium

Sodium concentrations from the three treatments showed little significant difference for the 1973 period. Fredriksen (1970) also reported only minor increases in sodium concentrations in a stream following clearcutting of a Douglas-fir watershed. Best and Monk (1974) reported average sodium concentrations of 1.1 mg/1 from a hardwood site and 1.3 mg/1 from a thirteen-year-old white pine site in soil-water samples at a depth of 25 cm. Concentrations from the white pine watershed are similar to those reported in the present study.

Reported average stream concentrations from eastern deciduous forests are about 0.9 mg/1 while annual outputs are in the range of 8 to 10 kg/ha (Best and Monk, 1974; Johnson and Swank, 1973; Likens, et al., 1970). Stream concentrations from western coniferous forest have been reported from 1.2 to 2.7 mg/1 (Fredriksen, 1970; Stottlemyer, 1968), while annual outputs ranged from 20 to 34 kg/ha (Fredriksen, 1970, 1972; Grier and Cole, 1972).

The greater losses of sodium from the two clearcuts during 1973 are almost entirely accounted for by increased water movement from these treatments. Fredriksen (1970) reported average annual losses of sodium for the first year following clearcutting that were 1.6 times greater than from a control watershed although average annual stream concentrations were approximately the same for the two treatments. The relative losses reported from the two clearcuts during the present study are almost identical to those reported by Fredriksen.

Sodium concentrations during the 1974 sampling period showed greater significant differences which could be due in part to the different precision with which these results were reported.

Sodium is generally not considered an essential element for plants (Pratt, 1965b), although it may be essential for some marine and blue-green algae (Devlin, 1966). The slight concentration increase that could result following clearcutting would probably have little or no effect on freshwater biota.

Phosphate

Concentrations of phosphate from all treatments were very low during 1973 in comparison to other solutes measured. Variability within a given set of samples was relatively high which suggests the precision of the method may have been low.

The grand mean concentration is lower than that reported by Cole, et al.,(1961) at a depth of 28 inches from a Douglas-fir site. Their results were for a period from January to July, which may account for the difference since our samples were taken during the growing season and

the concentrations should probably be lower than during the winter and spring months. Fredriksen (1970) reported average stream concentrations of phosphate of 0.016 to 0.026 mg/1 from an undisturbed Douglas-fir watershed.

Fredriksen (1970) reported that during the first year following clearcutting of Douglas-fir the average stream concentration from the cut watershed decreased slightly, while for the first year following slash burning (second year after clearcutting) average stream concentrations were about 2.4 times greater than from a control stream.

Total annual losses of phosphates appear to be very small from undisturbed watersheds. Reported losses have been about 0.18 kg/ha (Fredriksen, 1970), 0.5 kg/ha (Fredriksen, 1972), 0.02 kg/ha (Cole, et al., 1967), 2.0 kg/ha (U. S. Forest Service, 1971a), and 0.07 kg/ha for a period from January to July (Cole, et al.,1961). Following clearcutting, total phosphate losses have been reported to either increase or decrease slightly (Fredriksen, 1970; U. S. Forest Service, 1971a).

Soils data for phosphorus from our study exhibited considerable variation between years, but generally showed lower concentrations in all horizons from the 1965 clearcut. Herbaceous vegetation and tree reproduction on the 1965 clearcut, however, had significantly higher phosphorus levels than from the other two treatments. It is possible that the rapid utilization of phosphorus by understory vegetation on the two clearcuts reduces potential losses of this nutrient. The pattern of decreasing soil-water concentrations of phosphate during the summer tends to support this idea.

SUMMARY AND CONCLUSIONS

This manuscript reports data for chemical properties and biomass of forest floor and mineral soil horizons, understory vegetation, lodgepole pine trees, and logging residues in three treatment sites, as well as the concentrations and relative losses of selected ions in soil-water from the same three treatment sites during the summers of 1973 and 1974.

One site was clearcut in 1965, one was clearcut in 1972, and an additional site served as the undisturbed forest control. The objective of this study was to determine the effects of clearcutting on the distribution of nutrients and biomass and on the quantity and quality of water moving through the soil profiles in lodgepole pine forests on the eastern slope of the Front Range in Colorado.

Clearcutting is the removal of an entire forest stand in a single cut, and is the dominant timber harvesting practice in the Rocky Mountains of the western United States. Clearcutting was found to have a dramatic effect on the distribution of nutrients and biomass in the ecosystem components of forest floor, mineral soils, lodgepole pine trees, and understory vegetation. Significant effects on the nutrient concentrations in soil-water were also attributed to the clearcutting treatments.

Soils were strongly acid alfisols, with well-expressed organic and mineral horizons. There was a relatively large forest floor biomass in the undisturbed forest control site, indicating a slow cycling rate of these organic materials. Clearcutting almost doubled the O1 horizon biomass in the 1972 clearcut site, as a result of the influx of new litter materials following clearcutting, while the O2 horizon was little affected. The O2 horizon biomass in the 1965 clearcut was about half that in either of the

other two sites, and was probably a result of accelerated decomposition of organic materials of this horizon following cutting.

A highly leached A2 horizon formed the uppermost mineral soil horizon, and was above a strongly developed, extensive B2 horizon. Rocks and stone outcrops were common. Organic matter was low when compared to agricultural soils. The pH increased with depth, which seemed to be related to increasing levels of cation deposition, particularly Ca and Mg. Percent total N was highest in forest floor horizons, and decreased with depth, paralleling the trend of organic matter. Nitrate-N also decreased with depth in the organic horizons to non-detectable amounts in mineral horizons.

A one-way analysis of variance was used to test the null hypothesis of no difference between treatment sites. Statistical comparisons of soil and forest floor nutrient contents between sites were difficult to interpret due to high inherent variability, as well as differences in sample numbers and procedures between years. There were, however, some significant soil chemical differences between sites.

Nutrient levels in mineral soils of the 1972 clearcut did not show an immediate detectable response to clearcutting. The 1965 clearcut, however, appeared to have lower available P and percent organic matter levels, and higher pH levels and levels of exchangeable Ca and Mg. Forest floor horizons in the 1965 clearcut had lower total N, nitrate-N, and exchangeable K. Lower nutrient levels in the 1965 clearcut organic horizons was probably related to the nature of these materials, since the forest floor in this site consisted predominantly of woody materials which have remained after eight years of decay.

The forest floor and underlying mineral soil were the major nutrient storage components of the forest ecosystem. Differences between sites of the estimates of nutrient amounts in the 01 and 02 horizons primarily reflected differences in the total biomass of these forest floor layers. There were larger amounts of Ca but smaller amounts of P in the mineral soils of the 1965 clearcut site as compared with the other two sites.

Understory vegetation species diversity was relatively low in the undisturbed lodgepole pine forest. The 1965 clearcut had a greater variety of herbaceous species and shrubs, which were exclusive to this site. Subalpine fir and Engelmann spruce were the important tree reproduction species in the undisturbed forest, while lodgepole pine was more important in the 1965 clearcut site. Good stocking of lodgepole pine regeneration followed clearcutting of this site, particularly in areas of disturbed mineral seedbeds.

Clearcutting the 1972 clearcut site reduced total understory biomass by 52 percent, evidently as a result of mechanical disturbance during logging operations. *Vaccinium scoparium*, the major understory species in the undisturbed lodgepole pine forest, showed a 54 percent decrease following clearcutting, and survived primarily where sheltered by logging residues or residual trees.

Subordinate vegetation was of minimal importance in the overall distribution of N, P, K, and Ca in the 1972 clearcut and forest control sites. However, understory vegetation in the 1965 clearcut accumulated from 2 to 9 times more of these nutrients than in corresponding vegetation from the other two sites. This was due not only to species differences between sites, but also to an apparent increased adaptive capacity of the same species to utilize the greater availability of nutrients. The

greater accumulation of nutrients in the developing biomass of successional species in the 1965 clearcut may be significant in terms of reducing potential nutrient losses following clearcutting.

Total biomass of logging residues in the 1965 clearcut was about one-fourth that in the 1972 clearcut. This difference was due primarily to the greater amounts of stems, branches, and needles in the 1972 clear-cut. It was speculated that the difference in slash biomass between sites was due to a smaller initial tree density in the 1965 site, rather than to decomposition, since there is an extensive period of time required for complete decay of stems and branches.

Logging residues from the 1965 clearcut evidently had lost much of their original nutrient contents, particularly K and Ca. This nutrient release might explain the relatively high soil levels of Ca in the 1965 clearcut. Logging residues from the 1972 clearcut had nutrient levels similar to those in live lodgepole pine trees, and accounted for a substantial quantity of the total site nutrients.

Regression equations were calculated from a range of sample trees selected from the stand, and were based on the relationship of D^2H (d.b.h. squared times height) to stem biomass or branch, twig, and cone biomass, and between DH (d.b.h. times height) for needle biomass estimations. Correlation coefficients were high for each of the three allometric models, ranging from 0.838 to 0.971. High correlation coefficients might have reflected the nearly uniform stem and crown geometry of the trees composing these homogeneous, even-aged lodgepole pine stands. The actual tree harvest from the 1972 clearcut represented about 59 percent of the biomass that would be removed in a "whole tree" harvest, where branches and needles would be removed along with tree stems.

Determinations of nutrient levels in lodgepole pine tree components revealed that the highest concentrations of N, P, K, and Ca were in the needles and branches and twigs. Bark also had relatively high concentrations, particularly for Ca. Wood was typically low in most nutrients. The distribution of these nutrients appeared to reflect the functions and the proportion of living cells of the various lodgepole pine tree components.

Sizeable amounts of nutrients can be removed from the forest ecosystem as a result of clearcut timber harvesting and subsequent removal of the merchantable timber. Lodgepole pine trees in the 1972 clearcut prior to clearcutting accounted for 12 percent of the total ecosystem N, 16 percent of the P, 25 percent of the K, and 14 percent of the Ca. Again, "total" ecosystem values for N, P, K, and Ca were based on total N but available P, K, and Ca in forest floor and mineral soil components. It was estimated that when this site was clearcut, about five percent of the total N pool of the site was removed from the site as part of the merchantable harvest of tree boles and bark. In addition, seven percent of the "total" P, 10 percent of the "total" K, and six percent of the "total" Ca was removed, ignoring inputs from organic matter decomposition, mineral weathering, and precipitation. A considerable quantity of these nutrients were deposited on the forest floor in the logging residues, more than doubling the amount of P and K in the forest floor.

The proportions of nutrients stored in the mineral soil were much larger than those in trees or the forest floor. Total reserves in the upper 30.5 cm of mineral soil of total N, available P, and exchangeable K and Ca were from 6 to 13 times greater than the amounts removed in the

conventional clearcut harvest at the end of the 200-year rotation. The amount of total N removed by the bole harvest represented about 8 percent of the total soil N, 11 percent of the available soil P, 16 percent of the exchangeable soil K, and 8 percent of the exchangeable soil Ca. There appeared to be sufficient soil reserves of nutrients to support 12 similar tree rotations for N, 9 rotations for P, 6 rotations for K, and 13 rotations for Ca. Thus the nutrients which appeared to be most rapidly depleted from available soil reserves in the 1972 clearcut were K and P. If harvest of all trees 12.7 cm or 2.5 cm in diameter at breast height had occurred, quantities of nutrients removed would have correspondingly increased, and if a "whole tree" harvesting procedure had been used, the quantities of nutrients removed from the site would more than double.

Total water yields from both the 1972 and 1965 clearcuts were greater than from the control for both sampling years and yields from the 1972 clearcut were consistently greater than from the 1965 clearcut during both years. Water yields followed patterns similar to those reported in the literature for other clearcutting operations. Increased yields from the two clearcuts can be explained by reductions in evaporation (interception) and transpiration following removal of the forest. Water yields from the clearcuts were dramatically greater during the periods of high biological activity from late July to mid-September.

Increased water yields have special significance to streams draining these areas. If flows in these streams can be increased during periods of normally low water, then the carrying capacity of these streams could be increased if suitable space was a limiting factor. Clearcutting may also

result in a desynchronization of snow melt and tend to smooth out stream hydrographs which could reduce damage to stream biota caused by spring floods (channel scouring, bank erosion, sedimentation).

Increased water yields would also increase nutrient losses from clearcut sites by reducing the time solutes are in contact with exchange sites in the soil and plant roots. Additionally, if clearcutting resulted in conditions (i.e., temperature, moisture and light,) that were more favorable for microflora and fauna populations, then losses in excess of those normally occurring might be expected due to increased nutrient mobilization by these organisms.

Nitrogen losses from the three treatments provide the most dramatic example of clearcutting effects on nutrient losses in soil-water. Total nitrate losses were significantly greater from the two clearcuts than from the control during both sampling years, while ammonium losses were significantly less from the two clearcuts.

Nitrate concentrations from the 1972 clearcut did not differ significantly from those of the control until almost one year following cutting, whereas, while ammonium concentrations were significantly less from the 1972 clearcut with the first sample in early June 1973. During the second year following clearcutting, nitrate concentrations from the 1972 clearcut greatly exceeded those from the 1965 clearcut.

A probable explanation for this apparent change in nitrogen metabolism following clearcutting is that populations of nitrifying bacteria required almost one year to attain population sizes that were great enough to produce quantities of nitrates in excess of the demand by the heterotrophic communities. Ammonium concentrations decreased sooner than nitrates increased which probably was the result of almost immediate oxidation by nitrifying bacteria present prior to cutting.

Because anion adsorption in soil systems is only of very minor significance, any nitrate produced in excess of heterotrophic demands would be rapidly leached though the soil profile. Increased nitrate production coupled with higher water yields from the clearcuts resulted in a nitrate loss from the 1972 clearcut during the second year that was about fifteen times greater than from the control. Even eight years following clearcutting (1965 clearcut), nitrate losses during the summer were eleven times greater than from the control treatment.

Other studies of western coniferous systems (i.e. Douglas-fir) have not detected losses that appear as great as from our study. It is possible that these other studies were not continued long enough to allow soil bacterial populations to attain sufficient numbers. Other possible explanations for lower nitrate concentrations reported in other studies might be: stream biota are utilizing the increased nitrogen, and lowering stream concentrations; rapid revegetation on the site is utilizing the increased nitrates; or drainage from the cut watershed may only account for part of the measured stream flow. It is also possible that significant nitrification does not occur in some of these systems. Streams in our study area exhibited nitrate concentrations that were similar to the control concentrations even though some of them apparently drain large clearcut areas. It is likely that in our area, aquatic vegetation is rapidly utilizing the nitrates and that standard stream sampling procedures are inadequate to detect the changes evident in the soil-water analysis.

It is difficult to predict the consequences of increased nitrate additions to high mountain streams without knowing what nutrients may be limiting in the system. It has been suggested that since many of these streams are infertile, nutrient additions may be beneficial in stimulating production

at all levels within the system. The eventual addition of these nutrients to impoundments down stream that have slow flow-through times may result in eutrophication rates in excess of the natural condition.

Basic to understanding nutrient losses caused by clearcutting is how much of the most limiting nutrients are lost in relation to how much are totally available in the ecosystem. Many refinements are needed in calculating the nutrient budgets for these forest stands. Nutrient inputs into the system via mineral weathering, organic matter decomposition, and precipitation, and outputs via erosion are factors that need study in lodgepole pine forests of the Rocky Mountains. Little is known about rates of litter and logging residue mineralization, weathering rates for soil minerals, mobilization of nonexchangeable nutrient reserves, and precipitation inputs of nutrients that are available for uptake by vegetation. In addition, reliable estimates of soil content of rocks and boulders are needed. Values for nutrient contents of mineral soils would undoubtedly be lower if such corrections had been employed.

There is also a need for knowledge of the soil microflora and its role in the formation and decomposition of humus. For example, little is known about nitrification in forest soils or the fate of nitrates below the surface soil layers. It is not yet clear whether the thick organic layers found under many western conifer forests may generate nitrate at similar rates to the hardwood forest floor at Hubbard Brook following clearcutting. Reliable estimates for N-fixation and for denitrification in forest soils are needed to refine calculations of additions, losses, and reservoirs of N. It appears evident in this study that significant changes in nitrogen metabolism have taken place following clearcutting.

It would be a significant contribution to our understanding of the coniferous forest system if these changes could be documented. Additionally, it would be desirable to know how rapidly nitrogen is utilized by stream organisms and what concentrations are required to cause significant increases in the production of the various trophic levels present within the system.

In an undisturbed lodgepole pine system similar to that investigated during this study, sulfate, chloride, and probably bicarbonate appear to be the principal anions associated with cations in the soil-water solution. Following clearcutting, nitrate increases in importance in the ionic balance of the soil-water solution and the increase in the quantity of cations lost can be largely attributed to the increases in nitrate.

Calcium was the predominant cation measured in soil-water samples from all three treatments. Calcium also exhibited the greatest response to clearcutting of the cations measured. The increased calcium concentrations from the two clearcuts are probably the result of additions from slash which is suggested by the chemical analysis of the slash present on the two clearcut sites.

Higher losses of magnesium, potassium, and sodium from the two clearcuts were mainly due to increased water yields from these treatments. Although concentrations were statistically greater from the clearcuts during one or both years, differences were not large.

Chloride concentrations were lower from both clearcuts. Studies of eastern deciduous forests indicate that chloride budgets are almost balanced and very little storage occurs. If such is the case in the lodgepole pine systems investigated during this study, then an inverse concentration-volume relationship would explain the lower concentrations from the clearcuts.

Research is needed to determine if the bulk of the "available" P and exchangeable K and Ca located in the A2-B2 horizons is truly available to plants. There is a complex of reactions involved in nutrient absorption influenced by many factors. For example, K mobilization may involve simple water leaching, but with P or Ca a series of complex transformations may be necessary before absorption. The level of a particular nutrient in the plant is the result of a vast array of interactions between the plant and its atmosphere and rooting media (i.e., air composition, temperature, moisture; light quality and quantity; root media atmosphere, temperature, and moisture; and status of all macro- and micro-nutrients; as well as the metabolic activity of the tree). Lodgepole pine needles are the lowest in nutrient content of most tree species, reflecting the poor sites this species occupies.

This study emphasizes the accumulation of nutrients in the forest ecosystem, an outcome of storage in mineral and forest floor horizons as well as accumulation in the relatively large biomass of forest trees. Any management practice that reduces the vigor of the residual vegetation or delays regrowth of regeneration following cutting could increase nutrient loss rates. If there is rapid revegetation, potential nutrient losses from erosion and rapid leaching may be reduced. In addition, organic matter decomposition may be reduced to less than that in an exposed site.

Additional monitoring of the lodgepole pine system should be conducted to determine how long nutrient losses from clearcut sites exceed those from undisturbed areas and to estimate total losses over this period.

The effect of nutrient losses on future productivity is largely conjecture at present. There is need for more data on whether stands following clearcutting are any less productive biologically than those developed in partially cut or uncut forests. With the recent development of "whole tree" harvesting in some pulpwood stands there has been renewed interest in nutrient removal.

In any event, prolonged nutrient loss in soil-water leaching or limited revegetation on sites of low fertility may cause significant reductions in future nutrient-supplying capacities of forest ecosystems.

LITERATURE CITED

Adams, F. S., D. R. Mackenzie, H. Cole, Jr., and M. W. Price. 1971. The influence of nutrient pollution levels upon element constitution and morphology of Elodea canadensis Rich. Mich. Envir. Poll. 1:258-298.

Alexander, M. 1961. Soil Microbiology. John Wiley and Sons, New York. 472p.

Alexander, R. R. 1965. Growth of thinned, young lodgepole pine in Colorado. J. For. 63(6):429-433.

Alexander, R. R. 1966a. Establishment of lodgepole pine reproduction after different slash disposal treatments. USDA FS Rocky Mtn. For. and Range Exp. Sta. Res. Note RM-62. 4p.

Alexander, R. R. 1966b. Harvest cutting old-growth lodgepole pine in the central Rocky Mountains. J. For. 113-116.

Alexander, R. R. 1966c. Site indexes for lodgepole pine, with corrections for stand density: Instructions for field use. U. S. Forest Serv. Res. Paper RM-24. 7p.

Alexander, R. R., D. Tackle, and W. G. Dahms. 1967. Site indexes for lodgepole pine, with corrections for stand density: Methodology. U. S. Forest Serv. Res. Paper RM-29. 18p.

American Forest Institute. 1971. The effects of clearcut harvesting on forest soils--A summary of major research. Washington, D. C. 24p.

American Public Health Assoc. 1971. Standard methods for the examination of water and waste water. 13th edition. Amer. Pub. Health Assoc., Washington, D. C. 874p.

Anderson, T. D. and A. R. Tiedemann. 1970. Periodic variation in physical and chemical properties of two central Washington soils. USDA FS Pac. NW. For. and Range Exp. Sta. Res. Note PNW-125. 9p.

Art, H. W. and P. L. Marks. 1971. A summary table of biomass and net annual primary production in forest ecosystems of the world, pp.1-32. In Forest Biomass Studies, International Union of Forest Research Organization, Sec. 25: Yield and Growth. Univ. of Maine, Orono. 240p.

Attiwell, P. M. and J. D. Ovington. 1968. Determination of forest biomass. For. Sci. 14(1):13-15.

Basile, J. V. 1971. Site index for lodgepole pine--a poor indicator of site productivity for herbaceous plants. USDA FS Intermountain For. and Range Exp. Sta. Res. Note INT-152. 3p.

Basile, J. V. and C. E. Jensen. 1971. Grazing potential on lodgepole pine clearcuts in Montana, USDA Forest Serv. Res. Pap. Int-98. 11p.

Best, Ronnie G., and Carl D. Monk. 1974. Cation flux in a hardwood forest watershed and an eastern white pine watershed at Cowetta Hydrologic Laboratory. Unpublished paper.

Black, C. A. 1968. Soil plant relationships. 2nd Ed. John Wiley and Sons, New York. 792p.

Bolle, A. W., R. W. Behan, W. L. Pengelly, R. F. Wambach, G. Browder, T. Payne, and R. E. Shannon. 1970. A university view of the forest service. Prep. for Committee on Interior and Insular Affairs, U. S. Senate, Doc. 91-115., Washington, D. C. 33p.

Bollen, W. B., C. Chen, K. C. Lu, and R. F. Tarrant. 1967. Influence of red alder on fertility of a forest soil. Oregon State Univ. For. Res. Lab. Res. Bull. 12. 61p.

Bormann, F. H. and G. E. Likens. 1967. Nutrient cycling. Science 155:424-429.

Bormann, F. H., G. E. Likens, and J. S. Eaton. 1969. Biotic regulation of particulate and solution losses from a forest ecosystem. Bioscience 19(7): 600-610.

Bormann, F. H., G. E. Likens, D. W. Fisher, and R. S. Pierce. 1967. Nutrient loss accelerated by clearcutting of a forest ecosystem. pp.187-196. Young, H. E. (ed). In Symp. on Primary Productivity and Mineral Cycling in Natural Ecosystems. Univ. Maine Press, Orono.

Bormann, F. H., G. E. Likens, D. W. Fisher and R.S. Pierce. 1968. Nutrient loss accelerated by clearcutting of a forest ecosystem. Science. 159:882-884.

Bouyoucos, G. J. 1951. A recalibration of the hydrometer method for making mechanical analysis of soils. Agron. J. 43:434-438.

Boyle, J. R. and A. R. Ek. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. For. Res. 2(4):407-412.

Boyle, J. R., J. J. Phillips, and A. R. Ek. 1973. "Whole tree" harvesting: nutrient budget evaluation. J. For. 71(12):760-762.

Brehmer, M. L., R. C. Ball, and N. R. Kevern. 1969. Nutrients and primary production in a warm-water stream. Institute of Water Res. Mich. State University Tech. Report No. 4. Red Cedar River Series. 87p.

Bremner, J. M. 1965. Total Nitrogen. In Black, C. A. et al. (eds.). Methods of soil analysis, Part 2. Chemical and microbiological properties. Agronomy 9:1149-1178.

Brown,G. W.1972. Forest and water quality. Oregon State Univ. Bookstore. 74p.

Brown, G. W., A. R. Gahler, and R. B. Marston. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. Water Resour. Res. 9(5):1450-1453.

Brown, G. W., and J. T. Krygier. 1970. Effects of clearcutting on stream temperature. Water Resour. Res. 6(4):1133-1140.

Brown, G. W. and J. T. Krygier. 1971. Clearcut logging and sediment production in the Oregon Coast Range. Water Resour. Res. 7(5):1189-1199.

Brown, J. K. 1971. A planar intersect method for sampling fuel volume and surface area. For. Sci. 17(1):66-102.

Buchman, H. O. and N. C. Brady. 1969. The nature and properties of soil. 7th ed. Macmillan Co., New York. 653p.

Burns, J. W. 1972. Some effects of logging and associated road construction on northern California streams. Trans. Amer. Fish. Soc. 101(1):1-17.

Chapman, D. W. 1962. Effects of logging upon fish resources of the west coast. Jour. of Forestry 60(8):533-537.

Chapman, H. D. 1965. Cation-exchange capacity. In Black, C. A. et al., (eds.). Methods of soil analysis, Part 2,Chemical and microbiological properties. Agronomy 9:891-901.

Cochran, P. H. 1972. Temperature and soil fertility affect lodgepole and ponderosa pine seedling growth. For. Sci. 18(2):132-134.

Cole, D. M. 1971. A cubic foot stand volume equation for lodgepole pine in Montana and Idaho. USDA FS Intermtn. For. and Range Exp. Sta. Res. Note INT-150. 8 p.

Cole, D. M., and A. R. Stage. 1972. Estimating future diameters of lodgepole pine trees, USDA Forest Serv. Res. Pap. INT-131. 20p.

Cole, D. W. 1958. Alundum tension lysimeter. Soil Sci. 85:293-296.

Cole, D. W. and S. P. Gessel. 1965. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions, pp. 95-104. In Youngberg, C. T. (ed.), Forest-Soil Relationships in North America. Oregon St. Univ., Corvallis, Oregon.

Cole, D. W., S. P. Gessel, and S. F. Dice. 1968. Distribution and cycling of nitrogen, phosphorus, potassium, and calcium in a second-growth Douglas-fir ecosystem, pp. 197-232. In Young, H. E. (ed.), Symposium on Primary Productivity and Mineral Cycling in Natural Ecosystems. Univ. Maine Press, Orono.

Cole, D. W., S. P. Gessel, and E. E. Held. 1961. Tension lysimeter studies of ion and moisture movement in glacial till and coral atoll soils. Soil Sci. Soc. Proc. pp. 321-324.

Coleman, N. T. and G. W. Thomas. 1967. The basic chemistry of soil acidity. In Pearson, R. W. and F. Adams (eds.). Soil acidity and liming. Agronomy. 12:1-37.

Collett, B. M. 1963. Tree specific gravity of lodgepole pine from Colorado and Wyoming as affected by several growth factors. Master's Thesis, Colorado State University, Fort Collins, Colorado. 110p.

Cooper, C. F. 1969. Nutrient output from managed forests, pp. 446-463. In Eutrophication: Causes, Consequences, Correctives. Nat. Acad. Sciences. Washington, D. C.

Curlin, J. W. 1970. Nutrient cycling as a factor in site productivity and forest fertilization, pp. 313-325. In Youngberg, C. T. and C. B. Davey (eds.), Tree Growth and Forest Soils. Oregon State Univ., Corvallis.

Curry, R. R. 1971. Soil destruction associated with forest management and prospects for recovery in geologic time, pp.164-173. In "Clear-cutting" Practices on National Timberlands, Committee on Interior and Insular Affairs, U. S. Senate, 92nd Congress, 1st Session.

Curry, R. R. 1973. Geologic and hydrologic effects of even-age management on production of forest soils, particularly in the Douglas-fir region, pp. 137-178. In Hermann, R. K. and D. P. Lavender (eds.), Even-age Management Symposium, Oregon State University, Corvallis.

Dahms, W. G. 1966. Effect of kind and number of measured tree heights on lodgepole pine site-quality estimates. U. S. Forest Serv. Res. Pap. PNW-36. 8p.

Dahms, W. G. 1971. Growth and soil moisture in thinned lodgepole pine. USDA Forest Service Res. Pap. PNW-127. 32p.

Dahms, W. G. 1973. Tree growth and water use responses to thinning in a 47 year old lodgepole pine stand. USDA Forest Serv. Res. Note PNW 194. 14p.

Darnell, R. M. 1964. Organic detritus in relation to secondary production in aquatic communities. Verh. Int. Ver. Limnol. 15:462-470.

Daubenmire, R. F. 1943. Vegetational zonation in the Rocky Mountains. Bot. Rev. 9(6):325-393.

Daubenmire, R. 1953. Nutrient content of leaf litter of trees in the northern Rocky Mountains. Ecology 34(4): 786-793.

Day, P. R. 1965. Partical fractionation and particle size analysis. Black, C. A., D. D. Evans, J. L. White, L. E. Emsminger, F. E. Clark, and R. C. Dinauer (eds.). Methods of soil analysis, Part I. Physical and Mineralogical Properties, including Statistics of Measurement and Sampling. Agronomy 9:545-567.

DeByle, N. V. and P. E. Packer. 1972. Plant nutrient and soil losses in overland flow from burned forest clearcuts, pp. 296-307. In Watersheds in Transition, Amer. Water Resour. Assoc. Proc. Ser. 14, Urbana, Illinois.

Della-Bianca, L. and C. G. Wells. 1967. Some chemical properties of forest soils in the Virginia-Carolina Piedmont. U. S. For. Ser. Res. Pap. SE-28. 16p.

Devlin, R. M. 1966. Plant physiology. Reinhold Pub. Corp. N. Y. 564p.

Dickinson, C. H. and G. J. F. Pugh. 1974. Biology of plant litter decomposition. Vol. I. Academic Press, London. 146p.

Dils, R. E. 1971. Clearcutting in the forests of the Rocky Mountains. President's Council on Environmental Quality. 47p.

Dyrness, C. T. 1965. The effect of logging and slash burning on understory vegetation in the H. J. Andrews Experimental Forest. USDA FS Pac. NW For. and Range Exp. Sta. Res. Note 31. 13p.

Edmondson, W. T. 1970. Phosphorus, algae and nitrogen in Lake Washington after diversion of sewage. Science 169:690-691.

Elwood, J. W., and G. S. Henderson. 1973. Hydrologic and chemical budgets at Oak Ridge, Tennessee. Eastern Deciduous Forest Biome Memo Report #73-15. 38p.

Etter, H. M. 1969. Growth, metabolic components and drought survival of lodgepole pine seedlings at three nitrate levels. Can. J. Pl. Sci. 49(4):393-401.

Flower-Ellis, J. G. K. 1971. Age structure and dynamics in stands of bilberry (Vaccinium myrtillus L.). Dept. For. Ecol. Soils, R. Coll. For Res. Notes 9:1-108.

Forrest, W. G. 1969. Variations in the accumulation, distribution, and movement of mineral materials in radiata pine plantations. Ph.D. Dissertation, Australia Nat. Univ., Canberra. 276p.

Forrest, W. G. and J. D. Ovington. 1970. Organic matter changes in an age series of Pinus radiata plantations. J. Appl. Ecol. 7:177-186.

Foulger, A. N. and J. Harris. 1973. Volume of wood, bark, and needles after clearcutting a lodgepole pine stand. J. For. 71:93-95.

Frankland, J. C., J. D. Ovington, and C. MacRae. 1963. Spatial and seasonal variations in soil, litter, and ground vegetation in some lake district woodlands. J. Ecol. 51:97-112.

Frayer, Warren E. 1968. A computer program for making S-contrasts involving linear combinations of group means. U.S.D.A., For. Serv., Northwest For. Expt. Sta. Res. Note, NE-80. 6p.

Fredriksen, R. L. 1970. Comparative water quality--natural and disturbed streams, pp.125-137. In Morris, J. (ed.), Forest Land Uses and Stream Environment--Proc. of a Symp. Oregon State Univ., Corvallis.

Fredriksen, R. L. 1972. Nutrient budget of a Douglas-fir forest on an experimental watershed in western Oregon, pp. 115-131, In Proc.-- Research on Coniferous Forest Ecosystems--A Symp.. Pacific Northwest For. and Range Expt. Station. Portland, Oregon.

Geist, J. M. and G. S. Strickler. 1970. Chemical characteristics of some forest and grassland soils of northeastern Oregon. I. Results from reference profile sampling on the Starkey Experimental Forest and Range. USDA For. Serv. Res. Note PNW-137.

Gessel, S. P., and D. W. Cole. 1965. Influence of removal of forest cover on movement of water and associated elements through soil. J. Amer. Water Works Assoc. 57(10):1301-1310.

Gessel, S. P., D. W. Cole, and J. Turner. 1973. Elemental cycling and even-age forest management, pp. 179-198. In Hermann, R. K. and D. P. Lavender (eds.). Even-age Management Symp. Proc., Oregon State University, Corvallis.

Gibbons, D. R., and E. O. Salo. 1973. An annotated bibliography of the effects of logging on fish of the western United States and Canada. Pacific Northwest For. and Range Expt. Station. General Tech. Report, PNW-10. 145pp.

Gigon, A., and I. H. Rorison. 1972. The response of some ecologically distinct plant species to nitrate- and to ammonium-nitrogen. J. Ecol. 60:93-102.

Goodell, B. C. 1959. Management of forest stands in western United States to influence the flows of snow-fed streams. Int. Sci. Hydrol. Ass. Pub. 48:49-58.

Goodell, B. C. 1964. Water management in lodgepole pine type. Soc. Amer. Forest. Proc. (Denver, Colorado). p.117-119.

Gosset, D. R., and W. E. Norris, Jr. 1971. Relationship between nutrient availability and content of nitrogen and phosphorus in tissues of the aquatic macrophyte, Eichornia crassipes (Mart.) Salmo. Hydrobiologia 38:15-28.

Gosy, J. R., G. E. Likens, and F. H. Bormann. 1973. Nutrient release from decomposing leaf and branch litter in the Hubbard Brook Forest, New Hampshire. Ecol. Monographs 42:173-191.

Graham, E. R. 1959. An explanation of theory and methods of soil testing. Univ. Missouri Agr. Exp. Sta. Bull. 734. 17p.

Grier, C. C. and D. W. Cole. 1972. Elemental transport changes occurring during development of a second-growth Douglas-fir ecosystem, pp. 103-113. In Proc. Res. Conif. For. Ecosystems, Bellingham, Washington.

Hall, James D., and R. L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams, pp. 355-375. In T. G. Northcote (ed.), Symp. on Salmon and Trout in Streams. Univ. British Columbia. H. R. MacMillan Lectures in Fisheries.

Harridine, F. F. 1949. The variability of soil properties in relation to stage of profile development. Soil Sci. Soc. Am. Proc. 14:302-311.

Harris, A. S. 1972. Natural reforestation after logging on Afognak Island. USDA FS Pac. Northwest For. and Range Exp. Sta. Res. Note PNW-176. 11p.

Hatiya, K., K. Doi, and R. Kobayashi. 1965. Analysis of the growth in Japanese red pine (Pinus densiflora) stands. A Report on the Maturep Plantation in Iwate Prefecture. Government For. Exp. Sta. Bull (Tokyo) 176:75-88.

Heinrichs, J. F. 1954. Rapid specific gravity determinations. For. Prod. J. 4(1):68.

Hem, J. D. 1970. Study and interpretation of the chemical characteristics of natural water. U. S. Geol. Survey Water Supply Paper 1473. (2nd edition) 363 p.

Hewlett, J. D., and J. D. Helvey. 1970. Effects of forest clear-felling on the storm hydrograph. Water Resources Res. 6(3):768-782.

Hibbert, A. R. 1967. Forest treatment effects on water yield. Int. Symp. Forest Hydrol. Proc. Pergamon Press, N. Y. pp.527-543.

Hornbeck, J. W., and K. G. Reinhart. 1964. Water quality and soil erosion as affected by logging in steep terrain. J. Soil and Water Conserv. 19(1):23-27.

Hornbeck, J. W., R. S. Pierce, and C. A. Federer. 1970. Streamflow changes after forest cutting in New England. Water Resources Res. 6:1124-1132.

Howard, J. O. 1973. Logging residue in Washington, Oregon, and California--volume and characteristics USDA Forest Serv. Resour. Bull. PNW-44. 26p.

Howard, J. O. and F. R. Ward. 1972. Measurement of logging residue--alternative applications of the line intersect method. USDA FS Pac. NW For. and Range Exp. Sta. Res. Note PNW-183. 8p.

Hoyt, W. G., and H. C. Troxell. 1932. Forests and streamflow. Am. Soc. Civ. Eng. Proc. 56:1039-1666.

Hozumi, K., Y. Koyji, S. Kokawa, and T. Kira. 1969. Production ecology of tropical rain forests in southwest Cambodia. I. Plant biomass. Nature and Life in Southeast Asia 6:1-51.

Hynes, H. B. N. 1969. The enrichment in streams,pp. 188-196. In Eutrophication: Causes, Consequences, Correctives. Nat. Acad. Sciences. Washington, D. C.

Hynes, H. B. N. 1972. The ecology of running water. Univ. of Toronto Press. 555 p.

Ike, A. F. and J. L. Clutter. 1968. The variability of forest soils of the Georgia Blue Ridge Mountains. Soil Sci. Soc. Amer. Proc. 32(2):284-288.

Ingestad, T. 1973. Mineral nutrient requirements of Vaccinium vitis idaea and V. myrtillus. Physiol. Plant. 29:239-246.

Jackson, M. L. 1958. Soil chemical analysis. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. pp. 197-201.

Jackson, W. A. 1967. Physiological effect of soil acidity, pp.43-124. In Pearson, R. W. and F. Adams (eds.), Soil Acidity and Liming. Agronomy 12, Am. Soc. Agronomy, Madison, Wisc.

Jacob, W. C. and A. Klute. 1956. Sampling soils for physical and chemical properties. Soil Sci. Soc. Proc. 20:170-172.

Johnson, H. J. 1968. Pre-scarification and strip clearcutting to obtain lodgepole pine regeneration. For. Chron. 46(6):27-30.

Johnson, N. M., G. E. Likens, F. H. Bormann, D. W. Fisher, and R. S. Pierce. 1969. A working model for the variation in streamwater chemistry of the Hubbard Brook Experimental Forest, New Hampshire. Water Resour. Res. 5:1353-1363.

Johnson, O. D. and A. J. Cline. 1965. Colorado mountain soils. Adv. Agron. 17:233-281.

Johnson, P. L., and W. L. Swank. 1973. Studies of cation budgets in the southern Appalachians on four experimental watersheds with contrasting vegetation. Ecology 54(1):70-80.

Johnstone, W. D. 1971. Total standing crop and tree component distributions in three stands of 100-year-old lodgepole pine, pp. 81-89. In Forest Biomass Studies International Union of Forest Research Organizations. Section 25:Yield and Growth. Univ. Maine, Orono.

Keeney, D. R. 1972. The fate of nitrogen in aquatic ecosystems. Univ. of Wisc. Water Resources Center. Literature Review No. 3. 59 p.

Kiil, A. D. 1967. Fuel weight tables for white spruce and lodgepole pine crowns in Alberta. Can. Dep. Forestry and Rural Development, Dep. Pub. No. 1196. 13 p.

Kira, T. and T. Shidei. 1967. Primary production and turnover of organic matter in different forest ecosystems of the western Pacific. Jap. J. Ecol. 17:70-87.

Kochenderfer, J. N., and J. H. Patric. 1970. Effects of clearcutting--past and present on water resources of the Monongahela National Forest. W. Va. Agr. and For. 3(5):4-11.

Kovner, Jacob L. 1957. Evapotranspiration and water yields following forest cutting and natural regrowth. Soc. Am. For. Proc. 1956. pp.106-110.

Landis, T. D. 1972. An allometric model for bole biomass estimates of spruce and aspen in southwestern Colorado. Colorado State University Master's Thesis, Fort Collins, Colorado. 190p.

Levno, A., and J. Rothacher. 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. USDA For. Serv., Pacific Northwest For. Range Expt. Sta. Res. Note PNW-65. 12 p.

Likens, G. E., F. H. Bormann, and N. M. Johnson. 1969. Nitrification: importance to nutrient losses from a cutover forested ecosystem. Science 163(3872):1205-1206.

Likens, G. E., F. H. Bormann, N. M. Johnson, and R. S. Pierce. 1967. The calcium, magnesium, potassium, and sodium budgets for a small forested ecostystem. Ecology 48(5):772-785.

Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher, R. S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed ecosystem. Ecol. Monog. 40(1):24-46.

Little, Linda W. 1970. Phosphorus in water and wastewater. U. N. C. Wastewater Research Center Report No. 11. Chapel Hill, N. C. 126 p.

Lopushinsky, W. 1970. Relationship of needle surface area to needle volume in ponderosa pine and lodgepole pine. USDA FS Pac. NW For. and Range Exp. Sta. Res. Note PNW-126. 4 p.

Lutz, H. J. and R. F. Chandler, Jr. 1946. Forest soils. John Wiley and Sons, Inc., New York. 514p.

Lynch, James A., W. E. Sopper, and D. B. Partridge. 1972. Changes in streamflow following partial clearcutting on a forested watershed. In Watersheds in Transition, Amer. Water Resour. Assoc. Proc. Ser. 14, Urbana, Illinois.

Lyon, L. J. 1971. Vegetal development following prescribed burning of Douglas-fir in south-central Idaho, USDA Forest Serv. Res. Pap. INT-105. 30p.

Mader, D. L. 1963. Soil variability--a serious problem in soil-site studies in the northeast. Soil Sci. Soc. Amer. Proc. 27:707-709.

Madgwick, H. A. I. 1968a. Seasonal changes in biomass and annual production of an old-field Pinus virginiana stand. Ecology 49: 149-152

Madgwick, H. A. I. 1968b. The nutrient contents of old-field Pinus virginiana stands, pp. 275-282. In Youngberg, C. T. and C. B. Davey (eds.), Tree Growth and Forest Soils. Oregon State Univ., Corvallis.

Marks, P. L. and F. H. Bormann. 1972. Revegetation following forest cutting: mechanisms for return to steady-state nutrient cycling. Science 176(4037):914-915.

Marr, J. 1961. Ecosystems of the Front Range in Colorado. Univ. Colo. Studies Series in Bio. No. 8. 134p.

Martin, D. M., and D. R. Goff. No date. The role of nitrogen in the aquatic environment. Contributions from the Dept. of Limnol. Acad. of Nat. Sci. Philadelphia. No. 2. 46p.

Mason, D. T. 1915. The life history of lodgepole pine in the Rocky Mountains. USDA Bull. 154. 35p.

McColl, J. G. and D. W. Cole. 1968. A mechanism of cation transport in a forest soil. Northwest Sci. 42:134-140.

McConnell, William J. 1968. Limnological effects of organic extracts of litter in a southwestern impoundment. Limnol. and Oceanogr. 13(2):343-349.

McFee, W. W. and E. L. Stone. 1965. Quantity, distribution, and variability of organic matter and nutrients in a forest podzol in New York. Soil Sci. Soc. Amer. Proc. 29:432-436.

Meehan, W. R., W. A. Farr, D. M. Bishop, and J. H. Patric. 1969. Some effects of clearcutting on salmon habitat of two southeast Alaska streams. U.S.D.A., For. Serv., Pacific Northwest For. Range Expt. Sta. Res. Paper PNW-82. 45 p.

Megahan, W. F., and W. J. Kidd. 1972. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. J. For. 70(3):136-141.

Metz, L. J., C. G. Wells, and B. F. Swindel. 1966. Sampling soil and foliage in a pine plantation. Soil Sci. Soc. Amer. Proc. 30(3):397-399.

Metz, L. J., C. G. Wells, and P. P. Kormanik. 1970. Comparing the forest floor and surface soil beneath four pine species in the Virginia Piedmont. Southeast. Forest Exp. Sta., USDA Forest Serv. Res. Pap. SE-55. 8p.

Millar, C. E., L. M. Turk, and H. D. Foth. 1965. Fundamentals of soil science. Fourth Ed. John Wiley and Sons, Inc., New York. 491p.

Moir, W. H. 1969. The lodgepole pine zone in Colorado. Amer. Midl. Nat. 81(1):87-98.

Moir, W. H. 1972. Litter, foliage, branch, and stem production in contrasting lodgepole pine habitats of the Colorado Front Range, pp. 189-198. In Proc. Res. Conif. For. Ecosystems, Bellingham, Washington.

Moir, W. H. and R. Francis. 1972. foliage biomass and surface area in three Pinus contorta plots in Colorado. For. Sci. 18(1):41-45.

Moir, W. H. and H. Grier. 1969. Weight and nitrogen, phosphorous, potassium, and calcium content of forest floor humus of lodgepole pine stands in Colorado. Soil Sci. Soc. Am. Proc. 33(1):137-140.

Myers, C. A. 1964. Taper tables, bark thickness, and diameter relationships for lodgepole pines in Colorado and Wyoming. USDA FS Rocky Mtn For. and Range Exp. Sta. Res. Note RM-31. 6p.

Myers, C. A. 1967. Yield tables for managed stands of lodgepole pine in Colorado and Wyoming. U. S. Forest Serv. Res. Paper RM-26. 20p.

Myers, C. A. 1969. Board foot volumes to a 6 inch top for lodgepole pines in Colorado and Wyoming. USDA FS Rocky Mtn. For. and Range Exp. Sta. Res. Note RM-157. 3p.

Neal, J. R., E. Wright, and W. B. Bollen. 1965. Burning Douglas-fir slash: physical, chemical, and microbial effects in the soil. Forest Res. Lab. Oregon State Univ. 32 p.

Nelson, Daniel J., and Donald C. Scott. 1962. Role of detritus in the productivity of a rock-outcrop community in a Piedmont stream. Limnol. and Oceanogr. 7(3):396-413.

Nelson, L. E., G. L. Switzer, and W. H. Smith. 1968. Dry matter and nutrient accumulation in young loblolly pine (Pinus taeda L.), pp. 261-273. In Youngberg, C. T. and C. B. Davey (eds.), Tree Growth and Forest Soils. Oregon State Univ., Corvallis.

Ovington, J. D. 1953. Studies of the development of woodland conditions under different trees, I. Soil pH. J. Ecol. 41:13-34.

Ovington, J. D. 1962. Quantitative ecology and the woodland ecosystem concept. Adv. Ecol. Res. I:103-192.

Ovington, J. D. and H. A. I. Madgwick. 1959. Distribution of organic matter and plant nutrients in a plantation of scots pine. For. Sci. 5:344-355.

Ovington, J. D., W. G. Forrest, and J. S. Armstrong. 1968. Tree biomass estimation, pp. 4-31. In Young, H. E. (ed.), Symposium on Primary Productivity and Mineral Cycling in Natural Ecosystems. Univ. Maine Press, Orono.

Parizek, R. R., and B. E. Lane. 1970. Soil-water sampling using pan and deep pressure-vacuum lysimeters. Jour. Hydrol. 11:1-21.

Pierce, R. S., J. W. Hornbeck, G. E. Likens, and F. H. Bormann. 1970. Effect of elimination of vegetation on stream water quantity and quality, pp. 311-328. In IASH-UNESCO Symp., Results of Research on Representative and Experimental Basins, Wellington, N. Z.

Pierce, R. S., C. Wayne Martin, C. C. Reeves, G. E. Likens, and F. H. Bormann. 1972. Nutrient losses from clearcutting in New Hampshire, pp. 285-295. In Watersheds in Transition, Proc. Amer. Water Resources Assn. Ser. 14, Urbana, Illinois.

Pollard, R. A. 1955. Measuring seepage through salmon spawning gravel. J. Fish. Res. Board Can. 12(5):706-741.

Pratt, P. F. 1965a. Potassium. In Black, C. A. et al. (eds.), Methods of soil analysis, Part 2. Chemical and Microbiological Properties. Agronomy 9:1022-1030.

Pratt, P. F. 1965b. Sodium. In Black, C. A. et al. (eds.), Methods of soil analysis, Part 2. Chemical and Microbiological Properties. Agronomy 9:1031-1034.

President's Advisory Panel on Timber and the Environment. 1973. The impact of timber harvest on soil and water. Report of the President's Advisory Panel on Timber and the Environment. Arlington, Va. pp.427-467.

Ralston, C. W. and A. B. Prince. 1965. Accumulation of dry matter and nutrients by pine and hardwood forests in the lower Piedmont of North Carolina, pp.77-94. In Youngberg, C. T. (ed.), Forest-Soil Relationships in North America. Oregon State University, Corvallis, Oregon.

Reid, George K. 1961. Ecology of inland waters and estuaries. Reinhold Pub. Co. N. Y. 375 p.

Reinhart, K. G., and A. R. Eschner. 1962. Effect on streamflow of four different forest practices in the Allegheny Mountains. J. Geophys. Res. 67(6):2433-2445.

Remezov, N. P. 1958. Relation between biological accumulation and eluvial processes under forest cover. Soviet Soil Sci. 1958:587-598.

Remezov, N. P. 1961. Decomposition of forest litter and the cycle of elements in an oak forest. Soviet Soil Sci. 1961:703-711.

Remezov, N. P., Y. M. Samoylova, I. K. Sviridova, and L. G. Bogashova. 1964. Dynamics of the interaction of oak forest and soil. Soviet Soil Sci. 1964:222-233.

Remezov, N. P. and P. S. Pogrebnyak. 1965. Forest soil science. Eng. translation ed. by Israel Program for Scientific Translations Jerusalem, 1969. pp. 29-30, 159-167, and 181-183.

Rennie, P. J. 1965. The uptake of nutrients by mature forest growth. Plant Soil 7:49-95.

Rennie, P. J. 1966. A forest sampling procedure for nutrient-uptake studies. Comm. For. Rev. 45:119-127.

Retzer, J. L. 1961. Soil Survey--Trout Creek Watershed, Colorado. Series 1956 No. 20. USDA, For. Serv. and S.C.S., U. S. Govt. Printing Office, Washington, D. C. 47p.

Retzer, J. L. 1962. Soil Survey--Fraser Alpine Area, Colorado. Series 1956, No. 20. USDA, For. Serv. and S.C.S., U. S. Govt. Printing Office, Washington, D. C. 47p.

Rice, Elroy L., and Sunil K. Pancholy. 1973. Inhibition of nitrification by climax ecosystems. II. Additional evidence and possible role of tannins. Amer.J. Bot. 60(7):691-702.

Rothacher, J. 1970a. Increases in water yield following clearcut logging in the Pacific Northwest. Water Resources Res. 6(2):653-658.

Rothacher, J. 1970b. Regimes of streamflow and their modification by logging, pp.40-54. In Morris, J. (ed.), Forest and Land Uses and Stream Environment--Proc. of a Symp. Oregon State Univ., Corvallis.

Roussopoulos, P. J., and V. J. Johnson. 1973. Estimating slash fuel loading for several Lake States tree species. North Cent. For. Exp. Stn., St. Paul, Minnesota 8p.

Satoo, T. 1970. A synthesis of studies by the harvest method: primary production relations of the temperate deciduous forests of Japan, pp. 55-72. In Reichle, D. E. (ed.), Analysis of Temperate Forest Ecosystems. Springer-Verlag, New York.

Sawyer, C. N. 1947. Fertilization of lakes by agricultural and urban drainage. J. of the New England Water Works Assoc. 61:109-127.

Schneider, G. 1969. Biomass and macro-nutrient content in a 31-year-old black walnut plantation. Michigan Acad. II(94):33-41.

Seruya, C. and T. Berman. 1970. The evolution of nitrogen compounds in Lake Kinneret, pp. 73-78. In H. I. Shuval (ed.), Developments in Water Quality Research. Ann Arbor - Humphrey Sci. Publishers. 312p.

Shilova, Y. I. 1959. Five-year observations of qualitative composition of lysimeter water in various types of virgin and cultivated podzolic soils. Soviet Soil Sci. 1959:76-86.

Smith, Gilbert M. 1950. The fresh-water algae of the United States, McGraw-Hill Pub. N. Y. 719 p.

Smith, W. H., F. H. Bormann, and G. E. Likens. 1968. Response of chemoautotrophic nitrifiers to forest cutting. Soil Sci. 196(6):471-473.

Smithers, L. A. 1956. Assessment of site productivity in dense lodgepole pine stands. Can. Dep. Northern Affairs and Nat. Res., For. Branch, For. Res. Div. Tech. Note No. 30. 20p.

Soil Conservation Service, U. S. Department of Agriculture. 1967. Soil survey laboratory data and descriptions for some soils of Colorado. Soil. Surv. Invest. Rept. No. 10. 249p.

Soil Survey Staff. 1951, 1960. Soil Survey Manual and Supplement. U.S.D.A., S.C.S., U. S. Govt. Printing Office, Washington, D. C.

Soil Survey Staff. 1960, 1965, 1968. Soil Classification, 7th Approximation and Supplements. U.S.D.A., S.C.S., U. S. Govt. Printing Office, Washington, D. C.

Sokal, R. R. and F. J. Rohlf. 1969. Biometry. W.H. Freeman Co., San Francisco, Calif. 776p.

Stahelin, R. 1943. Factors influencing the natural restocking of high altitude burns by coniferous trees in the central Rocky Mountains. Ecology 24(1):19-29.

Stark, N. 1973. Nutrient cycling in a Jeffrey pine forest ecosystem. Montana For. and Conserv. Exper. Sta., Univ. of Montana, Missoula. 389p.

Stephens, F. R. 1966. Lodgepole pine soil relations in the northwest Oregon Cascade Mountains. J. For. 64(3):184-188.

Stottlemyer, J. R. 1968. Nutrient balance relationships for watersheds of the Fraser Experimental Forest. Ph. D. Thesis. Duke University. 104 p.

Stottlemyer, J. R. and C. W. Ralston. 1970. Nutrient balance relationships for watersheds of the Fraser Experimental Forest, pp. 359-382. In Youngberg, C. T. and C. B. Davey (eds.), Tree Growth and Forest Soils. Oregon State Univ. Pres. Corvallis, Oregon.

Swanston, D. N. 1971. Principal mass movement processes influenced by logging, road building, and fire, pp29-49. In Morris, J. (ed.), Forest Land Uses and Stream Environment--Proc. of a Symp. Oregon State Univ., Corvallis.

Switzer, G. L., L. E. Nelson, and W. H. Smith. 1966. The characterization of dry matter and nitrogen accumulation by loblolly pine (Pinus taeda L.). Soil Sci. Soc. Am. Proc. 30:114-119.

Subcommittee on Public Lands. 1971. Clearcutting practices on national timberlands. Hearings before Subcommittee of the Committee on Interior and Insular Affairs, U. S. Senate, 92nd Congress, 1st Session. 1247p.

Subcommittee on Public Lands. 1972. Clearcutting on federal timberlands. Report by the Subcommittee on Public Lands to the Committee on Interior and Insular Affairs, U. S. Senate, 92nd Congress, 2nd Session. 13p.

Tackle, D. 1962. Specific gravity of lodgepole pine in the intermountain region. Intermountain Forest and Range Exp. Sta. Res. Note No. 100. 4p.

Tadaki, Y., K. Hatiya, and K. Tochiaki. 1969. Studies of the production structure of forests. XV: Primary production of Fagus cirenata in plantation. J. Jap. For. Soc.51:331-339.

Tarrant, R. F. 1961. Stand development and soil fertility in a Douglas-fir-red alder plantation. For. Sci. 7(3):238-245.

Tarrant, R. F. 1971. Research on nutrient losses connected with forest management practices, pp. 932-934. In "Clear-cutting" Practices on National Timberlands, Hearings before the Subcommittee on Public Lands of the Committee on Interior and Insular Affairs, U. S. Senate, 92nd Congress, 1st session.

Trappe, J. M. 1959. Lodgepole pine clearcuts in northeastern Oregon. J. For. 57(6):420-423.

Trimble, G. R. and N. R. Tripp. 1949. Some effects of fire and cutting on forest soils in the lodgepole pine forests of the northern Rocky Mountains. J. For. 47:640-642.

U. S. Department of Commerce. 1973-74. Climatological Data---Colorado.

U. S. Forest Service. 1961. Handbook on Soils. U. S. Government Printing Office, Washington, D. C.

U. S. Forest Service. 1971a. Effect of forest-management practices on nutrient losses, pp. 1057-1067. In "Clear-cutting" Practice on National Timberlands, Hearings before the Subcommittee on Public Lands of the Committee on Interior and Insular Affairs, U. S. Senate, 92nd Congress, 1st Session.

U. S. Forest Service. 1971b. Forest management in Wyoming: Timber harvest and the environment in the Teton, Bridger, Shoshone, and Bighorn Forests. Wyoming Forest Study Team, C. M. Berntsen, Chairman, U. S. Dept. Agr. Forest Service. 80 p.

U. S. Forest Service. 1971c. Response to the report "Forest Management in Wyoming," Rocky Mountain and Intermountain Regions. U. S. Dept. Agr., Forest Service. 18 p.

Usher, M. B. 1970. Pattern and seasonal variability in the environment of a scots pine forest soil. J. Ecol. 58:669-679.

Vannote, Robin L. 1969. Detrital consumers in natural systems, pp. 20-23. In The Stream Ecosystem. A. A. A. S. Symp. Inst. of Water Res., Mich. State Univ. Tech. Report No. 7.

Vaux, Walter G. 1962. Interchange of stream and intergravel water in a salmon spawning riffle. U. S. Fish and Wildlife Serv. Spec. Sci. Report. Fish. 405. 11 p.

Verry, Elon S. 1972. Effects of an aspen clearcutting on water yield and quality in northern Minnesota, pp. 276-284. In Watersheds in Transition. Amer. Water Resour. Assoc. Proc. Ser. 14, Urbana, Illinois.

Vogl, R. J. and C. Ryder. 1969. Effects of slash burning on conifer reproduction in Montana's Mission Range. N. W. Sci. 43(3):135-147.

Vollenweider, R. A. 1967. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Organization for Economic Co-operation and Development. Committee for Research Co-operation. Paris. 194 p. (OECD Technical Report DAS/CSI/68.27).

Warren, E. E., J. H. Wales, G. E. Davis, and P. Doudoroff. 1964. Trout production in an experimental stream enriched with sucrose. J. Wildl. Mangt. 28(4):617-660.

Watanabe, F. S. and S. R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Amer. Proc. 29:667-668.

Waters, Thomas F. 1969. Production in natural stream systems, pp. 24-27. In The Stream Ecosystem. A.A.A.S. Symp. Inst. of Water Res., Mich. State Univ. Tech. Report No. 7.

Wellner, C. A. 1971. The scientific basis for silvicultural practices in forests of the northern Rocky Mountains, pp. 927-930. In "Clear-cutting" Practices on National Timberlands, Hearings before the Subcommittee on Public Lands of the committee on Interior and Insular Affairs, U. S. Senate, 92nd Congress, 1st Session.

Whittaker, R. H. 1961. Estimation of net primary production of forest and shrub communities. Ecology 42:177-180.

Whittaker, R. H. 1965. Branch dimensions and estimation of branch production. Ecology 46:365-370.

Whittaker, R. H. 1966. Forest dimensions and production in the Great Smoky Mountains. Ecology 47:103-121.

Whittaker, R. H. and G. M. Woodwell. 1968. Dimensions and production relations of trees and shrubs in the Brookhaven Forest, New York. J. Ecol. 56:1-25.

Whittaker, R. H. and G. M. Woodwell. 1969. Structure, production, and diversity of the oak-pine forest at Brookhaven, New York. J. Ecol. 57:155-174.

Wiklander, L. 1958. The soil, pp. 118-163. In Ruhland, W. (ed.), Encyclopedia of Plant Physiology, IV. Springer Verlag, Berlin.

Will, G. M. 1964. Dry matter production and nutrient uptake by *P. radiata* in New Zealand. Commonwealth For. Rev. 43:57-70.

Woodmansee, R. G. 1972. Soil descriptions and simulation model of potassium cycling in Colorado forests. Ph.D. Thesis. Colorado State University, Fort Collins, Colorado. 160p.

Woodwell, G. M., and R. H. Whittaker. 1967. Primary production and cation budget of the Brookhaven Forest, pp. 151-166. In Young, H. E., (ed.), Symposium on Primary Productivity and Mineral Cycling in Natural Ecosystems. Univ. Maine Press, Orono.

Wooldridge, D. D. 1968. Chemical and physical properties of forest litter layers in central Washington, pp. 327-337. In Youngberg, C. T. and C. B. Davey (eds.). Tree Growth and Forest Soils. Oregon State University, Corvallis, Oregon.

Yerkes, V. P. 1960. Occurrence of shrubs and herbaceous vegetation after clearcutting old growth Douglas-fir in the Oregon Cascades. USDA FS Pac. Northwest For. and Range Exp. Sta. Res. Pap. 34. 12p.

Young, H. E. and P. N. Carpenter. 1967. Weight, nutrient element and productivity studies of seedlings and saplings of eight tree species in natural ecosystems. Maine Ag. Exp. Sta. Tech. Bull. 28. 37p.

Youngberg, C. T. 1966. Forest floors in Douglas fir forests: I. Dry weight and chemical properties. Soil Sci. Soc. Amer. Proc. 30:406-409.

Youngberg, C. T. and W. G. Dahms. 1970. Productivity indices for lodgepole pine on pumice soils. J. For. 68(2):90-94.

Zinke, P. J. and W. L. Colwell, Jr. 1972. Nutrient cycling in forests. Proc. 1st Ann. Calif. Pl. E. Soil. Conf., Sacramento, California. 51:1972.

Zobel, B. J., J. H. Roberds, and J. Ralston. 1969. Drywood weight yields of loblolly pine. J. For. 67:822-824.

APPENDIX A

TECHNICAL DESCRIPTIONS OF SOIL PROFILES IN THE THREE LODGEPOLE PINE SITES ARE GIVEN BELOW. EACH PROFILE DESCRIPTION REPRESENTS EXAMINATION OF FOUR SOIL PITS PER SITE

Typical Profile of 1972 Clearcut Site[1]

Horizon	Depth	Description
01	5-3 cm	Mostly needles with some twigs, cones, and bark flakes of lodgepole pine; pH 4.4.
02	3-0 cm	Decomposed debris of plant material, copiously penetrated by small roots; pH 4.7.
A2	0-14 cm	Light yellowish brown (10 YR 6/2, dry) to dark reddish brown (5 YR 3/3, moist); structureless, single-grained; non-sticky, non-plastic, friable; pH 4.1; many roots; clear irregular boundary.
B2	14-68 cm+	Light yellowish brown (10 YR 6/4, dry) to dark brown (7.5 YR 4/2, moist); cobbly, gravelly sandy clay loam, distinct clay films on peds and pores; structureless, massive; slightly plastic, slightly sticky, friable; pH 4.4; a few roots present; many large stones.

Range in Characteristics

Thickness: 01 horizon 1 to 2 cm; 02 horizon 1 to 4 cm; A2 horizon 6 to 18 cm.

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[1]Soil profile descriptions completed prior to clearcutting.

Typical Profile of Undisturbed Forest Site

Horizon	Depth	Description
01	5-3 cm	Primarily needles with some twigs and cones of lodgepole pine; pH 4.3.
02	3-0 cm	Decomposing unrecognizable organic matter, held together as a mat by many small roots; pH 4.4.
A2	0-14 cm	Light yellowish brown (10 YR 6/2, dry) to dark reddish brown (5 YR 3/3, moist); charcoal present; gravelly sandy clay loam; structureless, single-grained, but slight tendency for granular structure; non-sticky, non-plastic, friable; pH 4.1; many roots; clear, irregular boundary.
B2	14-61 cm+	Light yellowish brown (10 YR 6/4, dry) to dark brown (7.5 YR 4/2, moist); cobbly, gravelly sandy clay loam, clay films complete and distinct on peds and in pores; structureless, massive; plastic, slightly sticky, friable; pH 4.4; few roots; mixed with coarse, weathered material and stones.

Range in Characteristics

Thickness: 01 horizon 1 to 6 cm; 02 horizon 1 to 6 cm; A2 horizon 12 to 15 cm thick.

Texture: A2 horizon sandy clay loam or clay loam.

Typical Profile of 1965 Clearcut Site

Horizon	Depth	Description
01	4-3 cm	Twigs, needles, cones, and bark flakes of lodgepole pine, with isolated accumulations or organic matter; pH 4.5.
02	3-0 cm	Needles, twigs, and bark fragments in advanced stages of decomposition, with noticeable amounts of mineral material and few roots; pH 4.8.
A2	0-17 cm	Light yellowish brown (10 YR 6/2, dry) to dark reddish brown (5 YR 3/3, moist); charcoal present; gravelly sandy clay loam; structureless, single-grained; non-plastic, non-sticky, friable; pH 4.4; many roots (many dead); diffuse, irregular boundary.
B2	17-101 cm+	Light yellowish brown (10 YR 6/4, dry) to dark brown (7.5 YR 4/2, moist); cobbly, gravelly sandy clay loam, clay films complete and distinct on peds and in pores; structureless, massive; plastic, sticky; pH 4.7; no roots; large boulders.

Range in Characteristics

Thickness: 01 horizon 0 to 1 cm thick; 02 horizon 0 to 6 cm thick; A2 horizon 9 to 27 cm thick.

Texture: A2 horizon sandy clay loam to loam;
B2 horizon sandy clay loam to clay loam.

APPENDIX B

MEANS, STANDARD DEVIATIONS, AND RANGES OF CHEMICAL PROPERTIES OF FOUR LODGEPOLE PINE SOIL HORIZONS FOR THREE CONSECUTIVE YEARS

Table 1

Hydrogen Ion Activity (pH)

Year	Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
1971	01	4.7±0.2 (4.6-4.8)	4.6±0.1 (4.4-4.7)	4.8±0.2 (4.6-5.0)	
	02	4.8±0.3 (4.5-5.1)	4.6±0.1 (4.5-4.8)	4.8±0.3 (4.6-5.2)	
	A2	5.3±0.2 (5.0-5.5)	4.6±0.9 (3.2-5.4)	5.2±0.3 (4.8-5.5)	
	B2	5.2±0.3 (4.9-5.6)	4.8±0.2 (4.7-5.0)	5.1±0.1 (4.9-5.2)	
1972	01	4.6±0.2 (4.2-4.9)	4.5±0.2 (4.1-4.8)	4.6±0.3 (4.1-5.1)	
	02	4.5±0.4 (3.9-5.1)	4.2±0.2 (3.8-5.1)	4.8[2]	
	A2	4.0±0.4 (3.4-4.8)	3.7±0.3 (3.3-4.2)	4.2±0.2 (3.7-4.4)	**
	B2	4.3±0.2 (3.6-4.6)	4.4±0.2 (4.0-4.7)	4.6±0.1 (4.3-4.8)	**
1973	01	4.4±0.2 (4.0-4.9)	4.3±0.2 (4.0-4.9)	4.5±0.3 (4.1-5.3)	
	02	4.7±0.4 (3.8-5.4)	4.4±0.3 (3.9-5.0)	4.8±0.2 (4.4-5.2)	**
	A2	4.1±0.3 (3.7-4.6)	4.1±0.3 (3.5-4.9)	4.4±0.3 (3.8-5.2)	**
	B2	4.4±0.2 (4.0-5.0)	4.4±0.3 (3.9-5.2)	4.7±0.4 (4.2-5.8)	**

[1]1971 and 1972 values prior to clearcutting, 1973 subsequent to clearcutting.

[2]Sample size of 1.

**Significant at $\alpha = 0.01$ level.

Table 2

Milliequivalents Per 100 Grams Cation Exchange Capacity

Year	Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
1971	01	74.0±1.6 (72.0-76.0)	70.5±3.9 (68.0-72.0)	70.2±4.3 (64.0-74.0)	
	02	66.8±5.9 (61.0-74.0)	72.2±3.8 (68.0-77.0)	56.3±8.5 (50.0-66.0)	*
	A2	6.0±0.6 (6.4-5.6)	8.5±2.6 (6.6-11.4)	-	
	B2	7.0[2]	11.6±1.2 (10.4-13.2)	10.4±2.5 (6.8-12.4)	
1972	01	-	-	-	
	02	-	-	-	
	A2	8.8±2.8 (4.7-15.2)	9.3±2.0 (6.6-13.0)	11.8±2.9 (6.3-17.3)	**
	B2	9.7±2.4 (6.2-14.8)	12.0±2.9 (4.8-17.2)	10.8±3.1 (5.6-15.2)	
1973	01	61.8±8.3 (46.0-78.0)	65.7±7.5 (39.0-87.0)	60.6±13.1 (35.0-83.0)	
	02	61.5±11.1 (40.0-84.0)	58.2±11.8 (34.0-82.0)	57.0±11.4 (36.0-77.5)	
	A2	8.3±2.0 (5.5-13.0)	9.9±3.4 (5.1-16.7)	8.9±3.0 (3.0-15.9)	
	B2	11.6±3.0 (6.9-17.6)	13.1±3.0 (7.4-17.8)	10.5±3.6 (3.8-17.6)	

[1]1971 and 1972 values prior to clearcutting, 1973 subsequent to clearcutting.

[2]Sample size of 1.

*Significant at $\alpha = 0.05$ level.
**Significant at $\alpha = 0.01$ level.

Table 3

Percent Total Nitrogen

Year	Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
1971	O1	0.98±0.03 (0.96-1.03)	1.01±0.08 (0.93-1.10)	0.90±0.07 (0.79-0.94)	+
	O2	1.01±0.13 (0.90-1.18)	1.12±0.07 (1.05-1.22)	0.74±0.14 (0.62-0.93)	**
	A2	0.04±0.00 (0.03-0.04)	0.05±0.02 (0.03-0.07)	0.03±0.01 (0.02-0.04)	
	B2	0.03±0.01 (0.02-0.04)	0.04±0.01 (0.03-0.04)	0.02±0.01 (0.01-0.03)	
1972	O1	0.99±.16 (0.76-1.48)	0.99±.14 (0.64-1.18)	0.85±.28 (0.41-1.23)	
	O2	0.96±.20 (0.62-1.39)	0.98±.14 (0.67-1.17)	0.88[2]	
	A2	0.05±.02 (0.02-0.09)	0.05±.02 (0.03-0.10)	0.06±.02 (0.02-0.09)	
	B2	0.03±.01 (0.02-0.04)	0.03±.01 (0.02-0.08)	0.03±.01 (0.01-0.05)	
1973	O1	0.88±0.21 (0.52-1.39)	1.06±0.13 (0.57-1.28)	0.95±0.30 (0.46-1.76)	**
	O2	0.92±0.23 (0.45-1.41)	0.89±0.25 (0.44-1.34)	0.81±0.20 (0.44-1.23)	
	A2	0.05±0.01 (0.04-0.09)	0.06±0.02 (0.03-0.12)	0.08±0.03 (0.04-0.19)	**
	B2	0.05±0.02 (0.03-0.12)	0.05±0.01 (0.03-0.08)	0.04±0.01 (0.02-0.07)	*

[1]1971 and 1972 values prior to clearcutting, 1973 subsequent to clearcutting.

[2]Sample size of 1.

+Significant at $\alpha = 0.10$ level.
*Significant at $\alpha = 0.05$ level.
**Significant at $\alpha = 0.01$ level.

Table 4

PPM Available Phosphorus

Year	Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
1971	01	50±9 (41-61)	62±7 (54-70)	52±5 (48-57)	+
	02	56±13 (47-74)	60±12 (48-77)	58±6 (55-66)	
	A2	17±4 (13-22)	29±9 (20-38)	22±10 (10-33)	
	B2	25±9 (11-31)	34±21 (18-65)	25±13 (9-41)	
1972	01	73±24 (46-140)	55±9 (40-77)	48±44 (18-180)	+
	02	56±15 (33-90)	39±10 (25-58)	42[2]	
	A2	28±17 (6-58)	22±7 (11-40)	20±8 (10-40)	+
	B2	23±13 (5-60)	29±15 (8-55)	16±9 (6-38)	**
1973	01	97±39 (40-195)	94±60 (30-220)	70±50 (15-285)	*
	02	77±33 (39-180)	63±33 (18-140)	43±24 (9-133)	**
	A2	20±9 (6-48)	23±12 (10-58)	18±6 (10-33)	+
	B2	37±13 (11-67)	37±15 (12-76)	23±12 (5-50)	**

[1]1971 and 1972 values prior to clearcutting, 1973 subsequent to clearcutting.

[2]Sample size of 1.

+Significant at $\alpha = 0.10$ level.
*Significant at $\alpha = 0.05$ level.
**Significant at $\alpha = 0.01$ level.

Table 5

PPM Exchangeable Potassium

Year	Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
1971	01	612±226 (392-900)	692±51 (650-750)	408±74 (298-450)	*
	02	644±286 (380-1000)	777±256 (478-1000)	363±26 (338-400)	+
	A2	84±33 (62-132)	87±34 (44-115)	94±49 (44-158)	
	B2	102±44 (65-158)	85±28 (55-115)	136±72 (48-220)	
1972	01	808±468 (430-2450)	650±280 (460-1650)	354±178 (165-750)	**
	02	665±290 (215-1300)	703±178 (412-988)	438[2]	
	A2	79±35 (15-150)	99±32 (48-165)	104±36 (62-210)	*
	B2	82±26 (42-127)	68±23 (28-115)	81±36 (40-200)	
1973	01	712±372 (106-2520)	588±138 (308-950)	572±390 (222-2640)	
	02	520±211 (175-1110)	419±182 (111-710)	386±134 (211-790)	**
	A2	90±37 (35-166)	127±86 (43-446)	109±34 (53-193)	*
	B2	105±44 (40-256)	109±43 (48-238)	102±51 (26-252)	

[1]1971 and 1972 values prior to clearcutting, 1973 subsequent to clearcutting.

[2]Sample size of 1.

+Significant at $\alpha = 0.10$ level.
*Significant at $\alpha = 0.05$ level.
**Significant at $\alpha = 0.01$ level.

Table 6

PPM Exchangeable Calcium

Year	Horizon	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
1971	01	2948±87 (2834-3033)	2834±583 (2295-3652)	3203±552 (2394-3612)	
	02	3392±867 (2554-4170)	3258±432 (2794-3771)	3228±1164 (1936-4649)	
	A2	319±107 (160-379	329±280 (80-718)	384±152 (160-499)	
	B2	519±284 (319-938)	444±160 (219-599)	474±19 (459-499)	
1972	01	4542±974 (3367-6132)	4741±1149 (3367-7254)	4164±952 (2625-5371)	**
	02	4463±1923 (2244-8377)	4176±1314 (2365-5872)	6363[2]	
	A2	348±140 (100-638)	278±167 (120-678)	495±299 (199-1058)	**
	B2	498±181 (80-918)	407±171 (60-638)	603±213 (199-1018)	**
1973	01	2308±668 (1162-3850)	2948±592 (2150-4850)	2801±744 (1338-4925)	**
	02	1637±865 (388-4938)	1662±716 (455-3225)	1649±816 (731-4375)	
	A2	295±104 (72-532)	279±153 (68-662)	515±261 (244-1375)	**
	B2	461±175 (198-905)	436±243 (62-1288)	515±221 (175-1032)	+

[1]1971 and 1972 values prior to clearcutting, 1973 subsequent to clearcutting.

[2]Sample size of 1.

+Significant at $\alpha = 0.10$ level.
**Significant at $\alpha = 0.01$ level.

APPENDIX C

MEANS, STANDARD DEVIATIONS, AND RANGES FOR CHEMICAL PROPERTIES OF LODGEPOLE PINE TREES, UNDERSTORY VEGETATION, AND LOGGING RESIDUES

Table 1

Lodgepole Pine Tree Components

Nutrient	Needles	Branches, Twigs and Cones	Branches and Twigs	Cones	Stems	Stem Bark	Stem Wood
Total Nitrogen (percent)	0.85±.06 (0.73-1.07)	0.34±.10 (0.23-0.50)	0.31±.06 (0.22-0.39)	0.29±.10 (0.20-0.52)	0.11±.02 (0.07-0.14)	0.25±.02 (0.21-0.28)	0.07±.01 (0.05-0.09)
Total Phosphorus (ppm)	778±56 (625-975)	382±72 (275-525)	490±170 (375-925)	289±87 (200-425)	78±25 (50-100)	474±47 (420-580)	114±25 (90-170)
Total Potassium (ppm)	2802±431 (1563-4750)	1114±252 (775-1613)	1418±394 (1000-2025)	800±297 (500-1175)	415±240 (275-1025)	1583±764 (528-2750)	320±39 (267-368)
Total Calcium (ppm)	2889±546 (1375-4500)	3278±562 (2250-4125)	2762±649 (1750-3625)	256±128 (125-500)	750±212 (500-1125)	6392±1364 (4400-8550)	804±151 (610-1025)

Table 2

Herbaceous Layer Vegetation

Nutrient	Year	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
Total Nitrogen (percent)	1972	0.99±.16 (0.82-1.50)	0.94±.09 (0.84-1.15)	1.35±.28 (0.97-1.77)	**
	1973	1.24±.18 (1.00-1.55)	1.37±.22 (1.08-2.18)	1.60±.57 (0.86-3.33)	+
Total Phosphorus (ppm)	1972	1015±193 (775-1575)	914±225 (375-1125)	1700±597 (1025-2700)	**
	1973	1041±213 (750-1600)	1161±226 (625-1675)	1852±719 (875-4350)	**
Total Potassium (ppm)	1972	2540±2181 (1663-10375)	2332±675 (1750-4088)	6709±4656 (2538-10375)	**
	1973	2635±750 (1500-4500)	3718±1016 (1750-5500)	10139±4428 (3750-19000)	**
Total Calcium (ppm)	1972	3980±610 (2700-5125)	4637±772 (3375-6625)	5125±3005 (2750-13625)	
	1973	3554±762 (2250-5000)	4489±902 (2125-6000)	4477±2052 (2375-10750)	

[1]1972 prior to clearcutting, 1973 subsequent to clearcutting.

+Significant at $\alpha = 0.10$ level.
**Significant at $\alpha = 0.01$ level.

Table 3

Tree Reproduction and Shrubs

Nutrient	Year	1972 Clearcut[1]	Forest Control	1965 Clearcut	F Test
Total Nitrogen (percent)	1972	0.63±.18 (0.43-0.84)	0.64±.16 (0.36-0.79)	1.06±.13 (0.94-1.18)	**
	1973	0.75±.28 (0.42-1.09)	0.78±.33 (0.23-1.35)	1.36±.77 (0.52-1.97)	**
Total Phosphorus (ppm)	1972	915±316 (575-1350)	878±296 (475-1275)	1306±131 (1225-1500)	**
	1973	838±348 (575-1150)	992±267 (375-1350)	1293±560 (900-1500)	**
Total Potassium (ppm)	1972	1765±755 (713-2463)	1538±895 (700-3250)	3903±938 (3150-5275)	**
	1973	3819±1308 (3000-5750)	3795±1225 (1250-6275)	6797±3897 (2750-8750)	**
Total Calcium (ppm)	1972	5130±1559 (2875-6750)	6762±3426 (4125-13250)	3831±1458 (2125-5200)	**
	1973	5583±1631 (3875-7125)	6731±3713 (2375-14625)	3798±2670 (750-10125)	**

[1]1972 prior to clearcutting, 1973 subsequent to clearcutting.

**Significant at $\alpha = 0.01$ level.

Table 4

Logging Residues

Nutrient	Slash Component	1972 Clearcut[1]	1965 Clearcut[2]	F Test
Total Nitrogen (percent)	Needles	0.88±.09 (0.77-0.99)	0.85±.17 (0.65-1.11)	
	Twigs	0.38±.18 (0.21-0.86)	0.21±.06 (0.15-0.30)	**
	Branches	0.20±.06 (0.12-0.29)	0.11±.02 (0.07-0.13)	**
	Stems	0.11±.02 (0.08-0.14)	0.08±.04 (0.06-0.15)	+
Total Phosphorus (ppm)	Needles	867±122 (725-1050)	688±179 (438-875)	*
	Twigs	290±118 (100-400)	210±55 (150-300)	**
	Branches	155±35 (100-200)	130±44 (75-188)	**
	Stems	125±66 (50-225)	95±14 (75-113)	**
Total Potassium (ppm)	Needles	2133±571 (1250-2750)	766±531 (298-1625)	**
	Twigs	858±452 (275-2000)	229±70 (160-333)	**
	Branches	715±306 (275-1275)	229±223 (108-625)	**
	Stems	555±110 (500-750)	167±88 (105-318)	**
Total Calcium (ppm)	Needles	2896±899 (2000-4125)	39±9 (28-52)	**
	Twigs	3112±1172 (1625-4625)	22±4 (15-25)	**
	Branches	2300±882 (1000-4000)	15±3 (12-19)	**
	Stems	500±342 (125-1000)	11±3 (7-15)	**

[1]9 months after clearcutting.

[2]7 years after clearcutting.

+Significant at $\alpha = 0.10$ level
*Significant at $\alpha = 0.05$ level.
**Significant at $\alpha = 0.01$ level.

APPENDIX D

WEEKLY MEAN CONCENTRATIONS, STANDARD ERRORS, AND SAMPLE NUMBERS FOR SOLUTES ANALYSED FROM "SHALLOW" LYSIMETERS AND PLATE LYSIMETERS FROM CLEARCUT TREATMENTS DURING 1973 AND 1974.

Table 1. Mean ammonium concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973.

Sampling Date	Depth	Treatment: Control Mean	Control S.E.[1]	Control N[2]	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06-73	10	---	----	-	---	----	-	.88	.332	4
	50	.01	.005	5	.11	.051	5	.05	.014	6
6-15-73	10	---	----	-	.55	----	1	1.13	----	1
	50	.02	.006	5	.06	.011	6	.10	.039	3
6-22-73	10	.69	----	1	.74	.302	2	1.16	----	1
	50	.01	.012	7	.04	.018	7	.12	.078	5
6-29-73	50	.04	.010	5	.07	.017	4	.43	----	1
7-06-73	10	---	----	-	1.59	----	1	2.05	.659	2
	50	.02	.014	3	.04	.015	5	.38	----	1
7-13-73	50	.03	.014	2	.06	.016	5	---	----	-
7-21-73	10	2.60	.542	3	---	----	-	3.42	.212	3
	50	.03	.015	2	.07	.001	2	.19	.188	2
8-17-73	50	.18	.074	2	.09	.035	2	.03	.028	2

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 2. Mean calcium concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973 and 1974.

		Treatment								
		Control			1972 Clearcut			1965 Clearcut		
Sampling Date	Depth	Mean	S.E.[1/]	N[2/]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	10	121.3	----	1	65.4	16.6	2	144.0	67.4	6
	50	4.4	0.6	6	6.9	1.2	8	7.2	1.7	7
6-22 + 29-73	10	66.0	20.3	3	31.9	0.6	2	28.8	2.0	4
	50	3.1	1.1	8	4.4	0.5	7	2.4	0.4	6
7-06 + 13-73	10	44.4	----	1	41.3	----	1	41.6	4.3	4
	50	3.0	0.9	7	3.0	0.8	6	6.1	0.4	3
7-21 + 27-73	10	42.3	5.0	3	71.0	30.4	2	27.4	4.1	4
	50	2.4	0.3	8	8.2	0.9	6	5.4	1.0	7
8-03 + 09-73	50	3.5	0.4	5	6.0	0.8	6	5.4	1.1	4
8-17 + 24-73	50	4.5	0.7	3	7.2	1.2	7	6.8	1.5	3
5-27-74	50	3	----	1	6	1.4	3	5	3.0	2
6-03-74	50	3	----	1	4	0.6	3	3	0.6	3

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 3. Mean magnesium concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973 and 1974.

Sampling Date	Depth	Treatment: Control Mean	Control S.E.[1]	Control N[2]	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06 + 15-73	10	228.2	----	1	22.2	12.8	2	25.5	8.2	6
	50	0.6	0.1	6	1.0	0.1	8	0.8	0.1	7
6-22 + 29-73	10	37.6	35.6	3	9.4	3.7	2	10.0	2.9	4
	50	1.3	0.6	8	0.5	0.1	7	0.5	0.1	6
7-06 + 13-73	10	10.8	----	1	0.5	----	1	10.5	3.3	4
	50	0.4	0.0	7	0.5	0.1	6	0.8	0.3	3
7-21 + 27-73	10	37.8	22.7	3	5.2	0.6	2	5.8	1.1	4
	50	0.8	0.0	8	0.8	0.1	6	1.5	0.2	7
8-03 + 09-73	50	0.7	0.0	5	1.1	0.1	6	1.3	0.3	4
8-17 + 24-73	50	0.8	0.1	3	1.5	0.2	7	1.4	0.6	3
5-27-74	50	1	----	1	2	0.3	3	1	1.0	2
6-03-74	50	1	----	1	1	0.0	3	1	0.0	3

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 4. Mean potassium concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973 and 1974.

Sampling Date	Depth	Treatment: Control Mean	Control S.E.[1]	Control N[2]	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06 + 15-73	10	2437.5	----	1	355.9	160.9	2	250.8	84.0	6
	50	0.8	0.2	6	1.7	0.8	8	2.4	0.6	7
6-22 + 29-73	10	857.2	427.5	3	94.2	61.8	2	164.7	56.6	4
	50	1.5	0.2	8	1.8	0.3	7	2.4	0.7	6
7-06 + 13-73	10	17.9	----	1	23.0	----	1	73.3	35.3	5
	50	1.6	0.2	7	2.3	0.5	6	2.2	1.0	3
7-21 + 27-73	10	398.3	197.1	4	136.4	126.9	2	18.2	12.4	4
	50	1.0	0.2	8	2.2	0.6	6	2.1	0.5	7
8-03 + 09-73	50	1.1	0.1	6	2.2	0.5	6	1.9	0.9	4
8-17 + 24-73	50	1.1	0.4	3	2.0	0.4	7	2.6	1.5	3
5-27-74**	50	1	---	1	1	0.3	3	0	0.5	2
6-03-74**	50	1	---	1	1	0.3	3	1	0.3	3

1/ Standard error of the mean.
2/ Number of samples analysed.
** Values reported to nearest mg. Values of less than 1 mg/l alternatively used as 0 and 1 to determine maximum deviation.

Table 5. Mean sulfate concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973.

Sampling Date	Depth	Treatment: Control Mean	Control S.E.[1]	Control N[2]	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06 + 15-73	10	1125.0	----	1	160.6	19.3	2	143.2	15.9	6
	50	2.1	0.6	6	4.2	1.6	8	3.2	0.8	7
6-22 + 29-73	10	153.3	134.6	3	31.9	14.4	2	22.3	5.4	3
	50	2.1	1.3	8	2.0	0.7	7	1.5	1.4	5
7-06 + 13-73	10	30.0	----	1	18.7	----	1	33.6	16.9	4
	50	2.0	0.4	7	2.8	0.6	6	4.4	1.3	3
7-21 + 27-73	10	258.0	218.0	3	69.5	59.5	2	17.7	10.5	4
	50	2.9	0.9	8	3.4	0.5	6	3.8	0.9	7
8-03 + 09-73	50	3.2	0.5	4	5.0	0.9	6	4.5	0.5	4
8-17 + 24-73	50	2.8	1.2	3	6.8	1.1	7	4.5	1.0	2

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 6. Mean chloride concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973.

Sampling Date	Depth	Treatment: Control Mean	Control S.E.[1]	Control N[2]	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06 + 15-73	10	80.1	----	1	12.8	7.1	2	20.6	8.1	6
	50	2.4	0.5	6	3.0	0.6	8	2.0	0.3	7
6-22 + 29-73	10	42.4	29.5	3	2.1	0.7	2	18.1	5.5	4
	50	1.9	0.2	8	1.8	0.3	7	3.3	0.9	6
7-06 + 13-73	10	5.0	----	1	6.4	----	1	8.0	3.2	5
	50	3.4	0.8	7	2.2	0.4	6	1.9	0.2	3
7-21 + 27-73	10	20.9	7.7	4	11.2	3.7	2	2.9	0.5	4
	50	2.1	0.3	8	2.7	0.2	6	1.8	0.2	7
8-03 + 09-73	50	3.1	0.8	6	2.I	0.3	6	1.9	0.2	4
8-17 + 24-73	50	4.3	----	1	2.6	0.6	7	4.3	1.5	3

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 7. Mean sodium concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973 and 1974.

		Treatment								
		Control			1972 Clearcut			1972 Clearcut		
Sampling Date	Depth	Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06 + 15-73	10	77.1	---	1	19.4	8.2	2	16.0	4.7	6
	50	1.6	0.4	6	2.0	0.4	8	2.5	0.3	7
6-22 + 29-73	10	37.9	18.4	3	4.7	1.5	2	7.5	2.0	4
	50	1.6	0.4	8	2.0	0.3	7	2.8	0.4	6
7-06 + 13-73	10	1.6	---	1	3.2	---	1	4.8	1.6	5
	50	1.8	0.2	7	2.5	0.4	6	2.7	0.2	3
7-21 + 27-73	10	19.5	8.4	4	7.4	4.3	2	2.2	0.4	4
	50	1.6	0.2	8	2.1	0.4	6	2.4	0.2	7
8-03 + 09-73	50	1.5	0.2	6	2.0	0.4	6	2.5	0.3	4
8-17 + 24-73	50	2.3	0.6	3	2.9	1.0	7	2.2	0.4	3
5-27-74	50	2	---	1	2	0.3	3	2	0.5	2
6-03-74	50	1	---	1	1	0.3	3	2	0.0	2

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 8. Mean phosphate concentrations (mg/l) in soil-water samples at 10 and 50 cm during 1973.

Sampling Date	Depth	Treatment								
		Control			1972 Clearcut			1965 Clearcut		
		Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06-73	10	---	----	-	---	----	-	.15	.026	4
	50	.02	.008	4	.03	.004	5	.03	.003	6
6-22-73	50	.02	.005	2	.01	.001	2	.05	.016	2
7-06-73	50	.02	.010	2	.01	.001	2	.03	----	1

1/ Standard error of the mean.
2/ Number of samples analysed.

Table 9. Mean specific conductance (μmhos/cm) in soil water samples at 10 and 50 cm during 1973 and 1974.

Sampling Date	Depth	Treatment: Control Mean	Control S.E.[1]	Control N[2]	1972 Clearcut Mean	1972 Clearcut S.E.	1972 Clearcut N	1965 Clearcut Mean	1965 Clearcut S.E.	1965 Clearcut N
6-06 + 15-73	10	7249	---	1	2410	820	2	1184	395	6
	50	44	5	6	68	9	8	60	8	7
6-22 + 29-73	10	3465	1649	3	1064	348	2	731	194	4
	50	39	9	8	45	5	7	49	8	6
7-06 + 13-73	10	310	---	1	81	---	1	393	98	4
	50	36	4	7	59	11	6	58	8	3
7-21 + 27-73	10	2006	838	4	884	631	2	259	52	4
	50	40	3	8	54	6	6	64	8	7
8-03 + 09-73	50	43	4	6	65	8	6	74	18	4
8-17 + 24-73	50	54	8	3	86	14	7	78	24	3
5-27-74	50	42	---	1	75	18	3	61	35	2
6-03-74	50	29	---	1	49	4	3	32	3	3

1/ Standard error of the mean.

2/ Number of samples analysed.

Table 10. Mean bicarbonate concentrations (mg/l) in soil-water samples at 10 and 15 cm during 1973 and 1974.

Sampling Date	Depth	Treatment								
		Control			1972 Clearcut			1965 Clearcut		
		Mean	S.E.[1]	N[2]	Mean	S.E.	N	Mean	S.E.	N
6-06-73	10	--	----	-	--	----	-	122	19.2	4
	50	15	0.7	5	25	5.0	5	22	3.1	6
7-21 + 27-73	10	305	117.7	4	40	----	1	119	8.0	4
	50	15	0.8	8	13	1.4	6	9	1.8	7
8-03 + 09-73	50	11	1.8	6	10	1.3	6	7	0.7	4
8-17 + 24-73	50	12	0.6	3	11	1.9	7	7	2.7	3
5-27-74	50	--	----	-	15	4.0	3	14	1.0	2
6-03-74	50	12	----	1	12	0.0	3	14	2.0	3

1/ Standard error of the mean.
2/ Number of samples analysed.

APPENDIX E

ANALYSIS OF VARIANCE RESULTS OF GRAND MEAN CONCENTRATIONS FROM "DEEP" LYSIMETERS FROM CLEARCUT TREATMENTS FOR THE 1973 AND 1974 SAMPLING PERIODS.

Table 1. Nitrate analysis of variance results for 1973 and 1974.

	Source	d. f.	Prop. S. S.*	F	α
1973	T**	2	.175	46.053	.005
	S°	1	.027	14.210	.005
	D+	1	.000		
	T x S	2	.046	12.105	.005
	T x D	2	.004		
	S x D	1	.001		
	T x S x D	2	.001		
	Error	400	.746		
	Total	411	1.000		
1974	T	2	.076	14.074	.005
	S	1	.039	14.444	.005
	D	1	.000		
	T x S	2	.036	6.667	.005
	T x D	2	.003		
	S x D	1	.000		
	T x S x D	2	.004		
	Error	316	.852		
	Total	327	1.000		

* Proportional sum of squares.
** Treatment
° Slope--two upper slope positions and the two lower slope positions combined.
+ Depth--75 cm and 100 cm.

Table 2. Ammonium analysis of variance results for 1973.

Source	d. f.	Prop. S. S.*	F	∝
T**	2	.057	9.194	.005
S°	1	.008	2.581	.250
D+	1	.018	5.806	.025!
T x S	2	.100	16.129	.005
T x D	2	.019	3.064	.100
S x D	1	.006	1.935	.250
T x S x D	2	.032	5.161	.025
Error	245	.760		
Total	256	1.000		

* Proportional sum of squares.
** Treatment
° Slope--the two upper slope positions and the two lower slope positions combined.
\+ Depth--75 cm and 100 cm.

Table 3. Calcium analysis of variance results for 1973 and 1974.

	Source	d. f.	Prop. S. S.*	F	α
1973	T	2	.085	12.879	.005
	S	1	.001		
	D	1	.005	1.515	.250
	T x S	2	.001		
	T x D	2	.002		
	S x D	1	.003		
	T x S x D	2	.002		
	Error	269	.901		
	Total	280	1.000		
1974	T	2	.147	14.135	.005
	S	1	.012	2.308	.250
	D	1	.004		
	T x S	2	.006		
	T x D	2	.004		
	S x D	1	.012	2.308	.250
	T x S x D	2	.005		
	Error	156	.810		
	Total	167	1.000		

* Proportional sum of squares.
** Treatment
° Slope--the two upper slope positions and the two lower slope positions combined.
+ Depth--75 cm and 100 cm.

Table 4. Magnesium analysis of variance results for 1973 and 1974.

	Source	d. f.	Prop. S. S.*	F	α
1973	T**	2	.000		
	S°	1	.003		
	D+	1	.002		
	T x S	2	.001		
	T x D	2	.009		
	S x D	1	.005	1.445	.250
	T x S x D	2	.010	.1.445	.250
	Error	269	.970		
	Total	280	1.000		
1974	T	2	.098	9.176	.005
	S	1	.040	7.491	.010
	D	1	.011	2.060	.250
	T x S	2	.006		
	T x D	2	.002		
	S x D	1	.011	2.060	.250
	T x S x D	2	.004		
	Error	155	.828		
	Total	166	1.000		

* Proportional sum of squares.
** Treatment
° Slope--the two upper slope positions and the two lower slope positions combined.
\+ Depth--75 cm and 100 cm.

Table 5. Potassium analysis of variance results for 1973 and 1974.

	Source	d. f.	Prop. S. S.*	F	∝
1973	T**	2	.019	2.794	.100
	S°	1	.001		
	D+	1	.002		
	T x S	2	.022	3.235	.050
	T x D	2	.008		
	S x D	1	.014	4.118	.025
	T x S x D	2	.008		
	Error	269	.926		
	Total	280	1.000		
1974	T	2	.102	11.591	.005
	S	1	.051	11.591	.005
	D	1	.076	17.273	.005
	T x S	2	.039	4.436	.025
	T x D	2	.041	4.659	.010
	S x D	1	.000		
	T x S x D	2	.002		
	Error	156	.689		
	Total	167	1.000		

* Proportional sum of squares.
** Treatment.
° Slope--the two upper slope positions and the two lower slope positions combined.
+ Depth--75 cm and 100 cm.

Table 6. Sulfate analysis of variance results for 1973.

Source	d. f.	Prop. S. S.*	F	α
T**	2	.081	11.571	.005
S°	1	.000		
D+	1	.001		
T x S	2	.008		
T x D	2	.000		
S x D	1	.002		
T x S x D	2	.002		
Error	259	.906		
Total	270	1.000		

* Proportional sum of squares.
** Treatment.
° Slope--the two upper slope positions and the two lower slope positions combined.
\+ Depth--75 cm and 100 cm.

Table 7. Chloride analysis of variance results for 1973.

Source	d. f.	Prop. S. S.*	F	α
T**	2	.072	11.250	.005
S°	1	.036	11.250	.005
D+	1	.019	5.938	.025
T x S	2	.025	3.906	.025
T x D	2	.014	2.188	.250
S x D	1	.002		
T x S x D	2	.002		
Error	260	.830		
Total	271	1.000		

* Proportional sum of squares.
** Treatment.
° Slope--the two upper slope positions and the two lower slope positions combined.
\+ Depth--75 cm and 100 cm.

Table 8. Sodium analysis of variance results for 1973.and 1974.

	Source	d. f.	Prop. S. S.*	F	α
1973	T**	2	.011	1.719	.250
	S°	1	.013	4.062	.050
	D+	1	.007	2.188	.250
	T x S	2	.092	14.375	.005
	T x D	1	.004		
	S x D	1	.000		
	T x S x D	2	.003		
	Error	268	.870		
	Total	279	1.000		
1974	T	2	.029	2.636	.100
	S	1	.043	7.818	.005
	D	1	.010	1.818	.250
	T x S	2	.053	4.818	.010
	T x D	2	.002		
	S x D	1	.004		
	T x S x D	2	.001		
	Error	156	.858		
	Total	167	1.000		

* Proportional sum of squares.
** Treatment.
° Slope--the two upper slope positions and the two lower slope positions combined.
+ Depth--75 cm and 100 cm.

Table 9. Phosphate analysis of variance results for 1973.

Source	d. f.	Prop. S. S.*	F	α
T**	2	.033	2.160	.250
S°	1	.000		
D+	1	.104	13.612	.005
T x S	2	.015		
T x D	2	.005		
S x D	1	.009		
T x S x D	2	.017		
Error	107	.817		
Total	118	1.000		

* Proportional sum of squares.
** Treatment.
° Slope--the two upper slope positions and the two lower slope positions combined.
+ Depth--75 cm and 100 cm.

Table 10. Water analysis of variance results for 1973 and 1974

	Source	d. f.	Prop. S.S.*	F	α
1973					
	T**	2	.030	10.714	.005
	S°	1	.000		
	D+	1	.002	1.429	.250
	TS	2	.000		
	TD	2	.005	1.786	.250
	SD	1	.000		
	TSD	2	.005	1.786	.250
	Error	695	.958		
	Total	706			
1974					
	T	2	.053	7.361	.005
	S	1	.002	.556	
	D	1	.001	.278	
	TS	2	.036	5.000	.010
	TD	2	.005	.694	
	SD	1	.014	3.889	.025
	TSD	2	.067	9.306	.005
	Error	228	.822		
	Total	239			

* Proportional sum of squares.
** Treatment.
° Slope--the two upper slope positions and the two lower slope positions combined.
+ Depth--75 cm and 100 cm.